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ORIGIN OF NORTH AMERICAN SALT DOMES

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ABSTRACT

A critical review of American thought on salt-dome origin shows that from the discovery of American salt domes in 1862 until the establishment of their economic importance by the development of a cap-rock pool at Spindletop in 1901, little was known of the constitution of the domes except what little was expressed at the surface. The result was a wide variety of highly speculative theories of origin, chief of which, as best fitting our meager knowledge, was the theory that the domes were old Cretaceous islands in Tertiary and even Recent seas.

Exploration of the known domes for cap-rock pools and sulphur deposits from 1901 to 1916-18 made us better acquainted with the salt, anhydrite, gypsum, limestone, sulphur, and various minor minerals—the salt-dome materials—and theories of deposition from solution became the vogue.

The development of important oil deposits in the lateral sands flanking the salt masses, from 1912 to date, concentrated attention on the structural features of the dome. The deposition-from-solution and lifting-power-of-crystallization theories seemed to be inadequate to explain the sharp and considerable uplift caused by the formation of the salt core and cap rock, and, with a growing recognition of the similarity of American salt domes to the salt structures of Germany, Roumania, Mexico, and elsewhere, came a gradual swing to the theory of tectonic origin.

This theory of tectonic origin supposes that the plastic salt was forced by pressure to flow from originally bedded deposits into its present position.

The author accepts the tectonic or pressure-flowage theory for the origin of American domes and believes that the most serious objection raised by its opponents—the lack of evidence as to the existence of sedimentary salt deposits—is no longer tenable in view of the recent discovery of potash salts and fossil algae in the salt core of the Markham dome.

INTRODUCTION

Great bosses and ridges of rock salt, differing from the more ordinary forms of bedded deposits, are known to occur in various areas of sedimentary rock throughout the world. These interesting salt masses, which, for lack of a better term broad enough to include

all varieties, may well be called "salt structures," are found in two regions of the North American continent: the Texas-Louisiana and Isthmus of Tehuantepec regions.

The Texas-Louisiana occurrences are of the plug or boss type generally called "salt domes." It is the purpose of the present paper to review the development of theories to account for the formation of this particular type of salt structure and to suggest what appears to the writer to be the most acceptable theory of origin.

A salt structure consists essentially of an anticline with a salt core, the structure of the enveloping rocks resulting in whole or part from the formation of the core. A salt dome is a very special form of salt structure having a circular or elliptical plane section.

The general use of the term "salt dome" is not entirely satisfactory except in the United States. "Salt anticline," "salt structure," or some similar term would seem to be more suitable for general application. The long salt ridges or anticlines of Mexico and Germany are in no sense domes, though apparently of similar origin, but it so happens that all of the salt structures known to date in the United States are true salt domes or salt plugs.

A salt structure consists essentially of the salt core, with or without cap rock, both of which are salt-structure material, and of the enveloping or abutting country rock to the extent to which its structure has been affected by the forces giving rise to the intrusion of the salt core.

The cores range in size and shape from shallow and flat to sharp and sometimes overturned ridges, miles in length, as in many of the European and Mexican structures; and from sharp to flat-topped conical plugs, of circular plane section, such as are so characteristic of the Gulf Coastal plain of the United States and of less common occurrence elsewhere.

The salt core may or may not be accompanied by a cap of massive anhydrite, or gypsum, limestone, dolomite, or of combinations of these with various minerals of minor importance including sulphur, selenite, calcite, galena, sphalerite, barite, pyrite, petroleum, etc. This cap rock of the coastal region—the *Gypshut* of the Germans —may be only a few feet or several hundred feet in thickness, and may be perched upon the top of the salt core, like the tip on a

billiard cue, as is common in the domes of the United States, or extend, thimble-fashion, down its sides, as in certain of the German and Mexican structures.

The structure of the sedimentary rocks overlying and adjacent to the salt and cap-rock core, when not complicated by faulting of independent importance and considerable magnitude, is apparently that caused by displacement sufficient to accommodate the intrusion of the salt and cap-rock core. The sedimentary rocks usually dip away from the salt.

The true salt dome is apparently an extreme or mature form of salt anticline, a conclusion which the writer is pleased to note is also put forward by Stille for German domes.

Salt structures are known to occur, outside of North America, in the general region of the Harz Mountains and the North German plain; on the south flank of the Carpathians and in the Transylvania Basin in Roumania; on the shores of the Red Sea in Egypt; in Southern Persia; and in Russia, Spain, Algeria, and Morocco. No occurrences have been described from South America though Pogue[1] calls attention to a possible salt structure in Colombia.

The two known salt structure regions in North America, one in the Texas-Louisiana province and the other in the Isthmus of Tehuantepec, Mexico, both lie within the coastal plain of the Gulf of Mexico.

As a speculation, it is suggested that salt structures will be found to be of much more common occurrence than is indicated by this catalogue. The type of structure is familiar to but few geologists and, lacking exploration by drill or shafts, may often be indistinguishable from other and more ordinary types of structure. A recently described salt deposit at Malagash, Novia Scotia,[2] has all the earmarks of a salt structure, but not enough is yet known to classify it definitely.

The better-known and more extensive Texas-Louisiana province includes two groups of domes. The coastal group occurs in the very flat lands of the coast along a strip extending inland about 70 miles

[1] J. E. Pogue, *Trans. Amer. Inst. Min. Eng.*, Vol. 65 (1921), p. 324.

[2] A. O. Hayes, "The Malagash Salt Deposit, Nova Scotia, Canada," *Dept. of Mines Geol. Surv., Memoir 121*, Ottawa, 1920.

from the Gulf of Mexico and from just west of the Mississippi to a short distance south of the Rio Grande. The interior group lies on the east flank of the Sabine uplift in northwestern Louisiana and in the syncline just west of the Sabine uplift in northeastern Texas. The interior group, as known at present, lies about 100 miles north of the coastal group. It might be subdivided into the Louisiana interior and the Texas interior groups, since these are separated by the Sabine uplift and lie some distance apart. Further study may indicate that this subdivision is of geologic as well as geographic importance.

The Isthmus of Tehuantepec province lies in the southeasternmost cantons of the state of Vera Cruz, Mexico, within a radius of 50 miles from the village of Minatitlan. It is much smaller in size than either the interior or coastal groups and is entitled to classification as a province only because it is an independent area and has an individual history and definite characteristics of its own.

The Texas-Louisiana domes are coming to be comparatively well known. The coastal group are but slightly expressed by surface geology, but are usually marked by a striking, if slight, topographic expression. They have been extensively explored by drill holes and mining operations. The interior domes are usually well expressed geologically and topographically, but have not been so extensively explored by the drill as have the domes of the coastal group.

The Tehuantepec salt structures are excellently expressed at the surface, both geologically and topographically. They have not been drilled so extensively as have the Texas-Louisiana domes, but the drilling has generally been more carefully directed and observed. In time, the study of the Tehuantepec area should yield more definite results than the study of the Texas-Louisiana area. The structures are better expressed at the surface.

AMERICAN THOUGHT ON SALT-DOME ORIGIN

The origin of salt domes has been a fruitful subject for controversy with American geologists since Thomassey, in 1860, first described the Five Islands and launched into the seas of speculation with his suggestion of volcanic origin. Much has been written and more has been said, often by men having at best an entirely inade-

quate knowledge, of the all too meager store of fact available to us regarding these interesting structures.

The development of American theories of salt-dome origin may be divided conveniently into three periods. The first period, extending to the time of the discovery of oil at Spindletop in 1901, was a time of casual theories, when next to nothing was known about the real constitution of the domes. Interest in them was casual and desultory and, as is always the case when exact information is too scarce to limit imagination seriously, widely different theories of origin were promulgated. Since the chief test for excellence in theory is that it shall not violate known fact, it is not surprising that a wide variety of theories should have been put forward.

The second period, marked by deposition from solution theories, extends from the determination of the great economic importance of these domes by the discovery of oil at Spindletop in 1901 to about 1916–18. The theories most favorably received were those attributing the origin of the domes to deposition from solution. This was the period of the development of the cap-rock pools and of development of the sulphur mines in the cap rock of the domes. Drilling operations added greatly to our knowledge of the domes, but the additions had largely to do with salt-dome material—the salt, limestone, gypsum, anhydrite, sulphur, and various minor minerals. Information as to the structure of the contiguous sediments was not entirely lacking, but much of it was presumptive evidence. The bulk of additions as to fact, and those most stressed, were observations regarding character, extent, and position of the dome materials—materials whose origin could most easily be explained by theories of deposition from solution.

The third period, which is one of structural theories, extends from 1916–18 down to the present. About 1914, exploration of the cap-rock areas of the known domes being practically complete, the rapid diminution of their economic importance was checked and interest in the domes was revived by the discovery of important oil deposits in the lateral sands flanking the salt masses. Salt domes which had been regarded as practically exhausted were rejuvenated as potential oil fields, and we are still in the period of exploring the flanks of the old domes as well as searching for new ones. The knowl-

edge of domes which has been developed as a result of this campaign has had to do mainly with the structure of the sedimentary rocks enveloping the salt and cap-rock mass. This information accents chiefly the upthrust which has been occasioned by the formation of the salt plug, and it is not surprising to see opinion trend to the theories of tectonic origin since they seem best to explain such structure.

Through all of these periods, like the chorus in a Greek tragedy, run constantly recurring theories of dome-origin as a result, direct or indirect, of volcanic activity. The theory of volcanic origin has never been generally accepted, has perhaps never even been adequately set forth, and, in the absence of some direct evidence of volcanic activity, seems to the writer to be more speculative than most other theories. It has, however, received favorable comment from many of the men best equipped, by an intimate knowledge of salt domes, to deal with the subject, and it can by no means be definitely and finally discarded.[1]

FIRST PERIOD (1860–1901); CASUAL AND RANDOM THEORIES

The main mass of rock salt at Petite Anse, Five Islands, was discovered during the deepening of one of the old brine wells in May, 1862. This was our first step toward a knowledge of the real structure of a North American salt dome.

The salt springs which are so often associated with the domes had been known to the early settlers and to the Indians, and had served as sources of brine for salt manufacture. Coxe,[2] in the early part of the eighteenth century, evidently referred to the salines of northern Louisiana in the statement: "There are many springs, pits and lakes, which afford most excellent common salt in great plenty, wherewith [the Indians] trade with neighboring nations for other commodities

[1] The writer has reviewed the theory of volcanic origin critically with unfavorable conclusions. See E. DeGolyer, "Theory of Volcanic Origin of Salt Domes," *Trans. Amer. Inst. Min. Eng.*, Vol. 61, pp. 456–69. New York, 1919.

[2] Daniel Coxe, A description of the English province of Carolina, by the Spaniards called Florida and by the French, La Louisiane, etc., 2d ed., London, 1726. Requoted from Harris and Veatch, *Historical Review*. A preliminary "Report on the Geology of Louisiana," *Geol. Surv. of Louisiana, Report for 1899, Baton Rouge*, which see for early references.

they want." Stoddard[1] notices and describes one of the Five Islands. He notes with regard to these islands that "some of them are impregnated with sulphur and one of them has been known to be on fire for at least three months." Travelers' tales! Darby[2] evidently visited Drake's and Bisteneau domes and described Petite Anse. He indulged in the first vague speculation as to origin, attributing the islands to a source other than "the revolution affected by alluvion."

Thomassy,[3] who visited the Five Islands in 1857 and 1859, describing them with some care, noting their similarity, alignment, and distinct characteristics, apparently suspected the presence of rock salt. After the discovery of the salt mass, he again visited Petite Anse,[4] and in announcing the finding of the salt, he reaffirmed the theory of volcanic origin, announced in his earlier work, "in the sense that it [Petite Anse] comes from a volcano of water, mud, and gas," and that the rock salt was formed from the evaporation of sea water by volcanic heat. Thomassy was impressed by the symmetry of the mounds and regarded the ponds found on them as being extinct crater types. He regarded the domes as akin to the mud lumps of the Mississippi delta and believed that he detected evidence of corrosion by thermal and acid waters on certain rocks found near Petite Anse which he supposed had been ejected from the depth of the gulf through explosive action.

Richard Owen,[5] while stationed with the Federal Army at New Iberia, in 1865, studied Petite Anse cursorily and concluded that the island was not of volcanic origin but that the salt was produced by the evaporation of sea water in barrier lagoons.

Goesmann,[6] in 1867, reported on the Petite Anse deposit. He re-

[1] Major Amos Stoddard, *Sketches, Historical and Descriptive of Louisiana.* Philadelphia, 1812.

[2] William Darby, *A Geographical Description of the State of Louisiana, etc.* Philadelphia, 1816.

[3] R. Thomassy, *Geologie pratique de la Louisiana.* Paris, 1860.

[4] R. Thomassy, "Supplement à la geologie pratique de la Louisiana, Île Petite Anse," *Societe Geologique de France, Bull. 20* (2d series, 1863), pp. 542–44.

[5] Richard Owen, "Report on Quaternary Rock Salt Deposits in Louisiana," *Trans. St. Louis Academy of Science,* Vol. 2 (1868), pp. 250–52.

[6] C. A. Goesmann and C. E. Buck, "On the Rock Salt Deposit of Petite Anse, Louisiana Rock Salt Co.," *Report of the American Bureau of Mines;* 35 pp., 2 pls. New York, 1867. Goesmann requoted from H. C. Bolton, *New York Academy of Science, Trans.,* Vol. 7, pp. 124–25. New York, 1888.

jected Owen's salt-plan theory and suggested that the salt resulted from the evaporation of brine springs rising through older deposits of bedded salt—a theory very similar to the later and more elaborate theories of Hill and Harris.

Hilgard,[1] in 1867, examined this same deposit at the request of Joseph Henry, of the Smithsonian Institution. He published a number of papers from 1869 to 1882, in addition to the one noted. Before this study, he suggested that the salt had been formed in lagoons but afterward he concluded that Petite Anse was not of volcanic origin, but that the Louisiana domes and salines were Cretaceous outliers with cappings of drift and other alluvial material. The present topographic form of the domes he regarded as the result of erosion; the various outliers as peaks on an old Cretaceous range; and the age of the salt as Cretaceous. He thought that any abnormal dips at the surface of the domes were the result of differential settling and suggested a genetic relationship between Petite Anse and the Calcasieu sulphur deposit.

Hopkins,[2] in reporting on the geology of Louisiana, held to views similar to those of Hilgard. He regarded the salines and domes as peaks on an old Cretaceous ridge, the salt as of Cretaceous age, and in commenting upon the common association of limestone, gypsum, sulphur, and petroleum, regarded the minerals as resulting from the reactions between buried organic matter and gypsum.

Lockett,[3] in 1870, visited the Five Islands. He considered them merely as the continuation of the Cote Gelee, Carenero, Grande

[1] E. W. Hilgard, "On the Geology of Lower Louisiana and the Salt Deposits of Petite Anse Island," *Smithsonian Contributions, Separate No. 248*, pp. 32–34. Washington, 1872.

[2] F. V. Hopkins, *First Annual Report of the Louisiana State Geological Survey; Annual Report of Board of Supervisors of the Louisiana State Seminary of Learning and Military Academy for the Year Ending Dec. 31, 1869*, pp. 77–109. New Orleans, 1870; *Second Annual Report of the Geological Survey of Louisiana to the General Assembly; Annual Report of the Board of Supervisors of the Louisiana State University for the Year Ending Dec. 31, 1870*, pp. 1–7. New Orleans, 1871; *Third Annual Report of the Geological Survey of Louisiana; Annual Report of D. F. Boyd, Superintendent Louisiana State University for 1871*, pp. 163–206. New Orleans, 1872.

[3] Colonel Samuel H. Lockett, *Report of the Topographical Survey of Louisiana, Louisiana State University; Report of Superintendent for 1870*, pp. 16–26. New Orleans, 1871.

Coteau, and Opelousas Hills; the whole at one time forming a great natural levee along the shores of an estuary occupying the Mississippi Valley. During a great flood a series of mighty crevasses were made in this levee, and thus the islands were formed.

Penrose,[1] in 1889, examined the Palestine dome, identified the outcrop of Cretaceous rocks and concluded that it "doubtless represents the remains of an island in the old Tertiary sea."

Herndon[2] described Books and Steen salines and regarded the former as an old Cretaceous island in the Tertiary seas.

Dumble[3] examined the Palestine dome in 1890. He regarded it as "only one of a series of these deposits of salt which seem to extend in two or more lines from northeast Texas in a southeasterly direction toward the Gulf." He lists all of the Texas interior group of salt domes which we know today except Keechi, and concludes that "they represent islands in the Tertiary sea formed by projecting eminences of the underlying strata of Cretaceous age."

Kennedy,[4] in 1892, described Grand Saline and seems to have escaped the idea, then orthodox among members of the Texas Geological Survey, that it was a Cretaceous outlier. He describes the dip of the rocks in some detail and refers to it as the "Grand Saline fold."

Lerch, in 1893, set forth the results of his observations of the geology, including that of the salines, in north Louisiana. In the first of his papers[5] he concludes that no volcanic eruptions and no violent contortions have disturbed the geological formations of north

[1] R. A. F. Penrose, "A Preliminary Report on the Geology of the Gulf Tertiary of Texas from the Red River to the Rio Grande," *First Annual Report, Geol. Surv. Texas* (1889), p. 101. Austin, 1890.

[2] J. H. Herndon, "Smith County (the Iron Ore District of East Texas)," *Second Annual Report Geol. Surv. Texas* (1890), pp. 222–24. Austin, 1891.

[3] E. T. Dumble, "Anderson County (the Iron Ore District of East Texas)," *ibid.*, pp. 303–17.

[4] William Kennedy, "A Section from Terrell, Kaufman County, to Sabine Pass on the Gulf of Mexico," *Third Annual Report Geol. Surv., Texas* (1891), pp. 41–125. Austin, 1892.

[5] Otto Lerch, "A Preliminary Report upon the Hills of Louisiana, North of the Vicksburg, Shreveport, and Pacific Railroad, Louisiana State Experiment Stations," *Geology and Agriculture*, Vol. 1 (1893), p. 27.

Louisiana; and in a second paper,[1] after stating that the existence of salines can only be traced along the summit of a Cretaceous ridge, which traverses the state diagonally from its northwest corner to the island of Petite Anse, arrives at a conclusion combining Hilgard's Cretaceous outlier theory and a theory similar to volcanic origin. It was his idea that at the close of Mesozoic time enormous plutonic forces had thrown up mountain chains of vast extent and that isolated peaks in the ranges so formed had been islands in the Tertiary sea. He also regarded the Balcones fault and the basaltic outbreaks along it as of contemporaneous origin.

Vaughan,[2] in 1895, in publishing the report of his own work in Louisiana, reviewed the papers of Hilgard and Lerch and expressed conformity with Hilgard's idea of a Cretaceous ridge. He failed to observe evidences of any orogenetic movement as postulated by Lerch.

Clendenin,[3] as a result of investigations during the summers of 1894–95, expressed the opinion with regard to Thomassy's theories that there was no evidence of volcanic activity. He followed Hilgard, whom he quotes extensively, but suggested, somewhat after Lerch, that the Cretaceous outliers are the result of differential elevation rather than differential erosion. He recognized clearly the earth movement during comparatively late geological time.

Harris and Veatch,[4] in 1899, published the first considerable studies of the Louisiana domes and salines. They regarded the Five Islands as "a series of very peculiar dome-shaped folds and, to all appearances, a large fault," formed in Quaternary or Recent time. The Cretaceous outcrops of northern Louisiana are regarded as "similar domes," but it "is hard to believe they were formed so recently" as the Five Islands. The Winnfield anticline indicates that

[1] "A Preliminary Report upon the Hills of Louisiana, South of Vicksburg, Shreveport, and Pacific Railroad to Alexandria, Louisiana, Louisiana State Experiment Stations," *ibid.*, Vol. 2, 53–109.

[2] T. Wayland Vaughan, "Stratigraphy of Northwestern Louisiana," *Amer. Geol.*, Vol. 15 (1895), pp. 208–29.

[3] W. W. Clendenin, "A Preliminary Report upon the Florida Parishes of East Louisiana and the Bluff, Prairie, and Hill Lands of Southwest Louisiana, Louisiana State Experiment Stations," *Geology and Agriculture*, Vol. 3 (1896), pp. 236–40.

[4] Gilbert D. Harris and A. C. Veatch, "A Preliminary Report on the Geology of Louisiana Geological Survey of Louisiana," *Report for 1899*, pp. 9–138. Baton Rouge.

part of the movement at least was post-Claiborne. They concluded against Hilgard's Cretaceous ridge and in favor of "northeast-southwest local folds parallel to old shorelines" to account for the domes.

Veatch,[1] in 1899, left off his study of the salines of north Louisiana to investigate the Five Islands. He reports that only two of the islands show indications of method and date of origin, Belle Isle showing a very distinct dome-shape fold and Petite Anse seeming to represent a fault block. He regarded the supposed faulting as possibly due to solution of the underlying salt, but more likely due to orographic movement. He concluded that the formations of the island possibly began with movement in late Tertiary time, evidence of which had thus far been seen only at Petite Anse; that the main folding and faulting occurred in the Pleistocene and was followed by the sinking of the whole coastal region and deposition of the upper yellow clays; that during a succeeding period of elevation, the deep channels of the coastal rivers were excavated and lake valleys formed in the island; and the subsidence which followed had continued to the present day.

Anthony F. Lucas, in 1896, discovered salt under Jefferson Island and thus initiated the most fruitful part of the prospecting and study of the coastal domes which culminated in his discovery of the Spindletop gusher in January, 1901. In 1896, in 1898, and in 1899 he published papers[2] on Louisiana salt, but was concerned with occurrence rather than origin, merely noting a belief that the geological formations of the Five Islands is Quaternary, that the salt is of Tertiary age, and appears to rest on the Cretaceous, and that the salt formation at Jefferson Island does not lie in undisturbed strata but seems to have been folded and contorted while still in a plastic condition. Lucas clearly recognized the dome structure of Spindletop, but is said to have thought it was due to gas pressure.[3]

[1] A. C. Veatch, "The Five Islands, Louisiana, Louisiana State Experiment Stations," *Geology and Agriculture*, Vol. 5 (1899), pp. 259–60, pls. 19–31.

[2] A. F. Lucas, "The Avery Island Salt Mine and the Joseph Jefferson Salt Deposit, Louisiana," *Eng. and Min. Jour.*, Vol. 62 (1896), pp. 463–64; "Louisiana Salt Resources," *American Manufacturer*, Vol. 63 (1898), pp. 910–11; "Rock Salt in Louisiana," *Trans. Amer. Inst. Min. Eng.*, Vol. 29 (1899), pp. 465–66.

[3] Robert T. Hill, "The Coast Prairie of Texas," *Science*, N.S., Vol. 14 (1901), p. 327.

Veatch,[1] in reporting on the salines of north Louisiana, expressed no substantial modification of his views as expressed for the Five Islands. He seems to have become quite definitely convinced of the anticlinal or domelike structure of the sedimentary rocks surrounding the salt cores; he recognized clearly the similarity of the coastal domes, both in Texas and Louisiana to the northern salines; and he published the first general Texas-Louisiana map showing an alignment of the domes.

Adams,[2] in 1901, after the discovery of Spindletop, published a preliminary report indicating many of the interior group of domes, which he maps as Cretaceous outliers, and lists many of the coastal domes as being prospected for oil. His paper does not show that he recognizes these occurrences as salt domes, though he states that Petite Anse and Grand Saline are probably similar types. He regards the salt as probably of Cretaceous age and republishes the F. V. Hopkins section through Petite Anse, Pine Prairie, and Winnfield.

SECOND PERIOD (1901–16); DEPOSITION FROM SOLUTION THEORIES

The theory of Goesmann was the first of the deposition from solution theories of salt-dome origin to be put forward, but it was promulgated at a time when the salt dome was little known and of almost no general interest. With the discovery of the Lucas gusher at Spindletop, however, and the completion of a survey of the Louisiana domes by Veatch, the domes began to receive more serious attention from geologists.

Harris[3] visited Spindletop shortly after the discovery and announced that the scanty evidence available indicated that the Lucas gusher was on a Cretaceous anticline, a theory which he regarded as corroborated by the log of the Higgins well.[4]

[1] A. C. Veatch, "The Salines of North Louisiana," *Geol. Surv. of Louisiana, Report of 1902*, pp. 47–100.

[2] George I. Adams, "Oil and Gas Fields of the Upper Cretaceous and Tertiary Formations of the Western Gulf Coast," *U. S. Geol. Surv. Bull. 184*, pp. 37–62. Washington, 1901.

[3] G. D. Harris, communication to *New Orleans Picayune*, March 27, 1901. Requoted from Harris, "Oil in Louisiana," *Geol. Surv. of Louisiana, Report of 1902*, p. 273.

[4] G. D. Harris, "Oil in Texas," *Science*, N.S., Vol. 13 (April 26, 1901), pp. 666–67.

Hill[1] at first thought that there was no structural disturbance and that wells might be drilled "with reasonable assurance that oil is apt to be found anywhere within the region of the coast plain above the oil-impregnated sands." He concluded "that oil should be found at decreasing depths at the rate of about seven to ten feet per mile along the line drawn from Beaumont to Oil City, in southern Nacogdoches County." After a visit to Damon Mound, however, he was convinced by Lucas that Spindletop was a true dome,[2] though he regarded the domes as "probably due to isostatic movements rather than accumulation of gas."

Hill, in 1902, published his theory on the formation of the domes by deposition from solution as follows:

> The oil and salt pockets of the Texas Coastal Plain are probably not indigenous to the strata in which they are found, but are the resultant products of columns of hot saline waters which have ascended, under hydrostatic pressure, at points along lines of structural weakness, through thousands of feet of shale, sand, and marine littoral sediments of the Coastal Plain section, through which oil and sand are disseminated in more or less minute quantities. The oil, with sulphur, may have been floated upward on these waters, and the salt and dolomite may have been crystallized from the saturated solution.
>
> The channels of these ascending waters may have been in places of structural weakness, such as fissures, which probably at one time continued to the surface, but may have been sealed by the deposition of the later overlapping strata now capping the oil pools.[3]

Hayes[4] reviewed Hill's theory, after making a study of the coastal region, and concluded that, while the theory was suggestive and worthy of careful consideration, it could not be accepted in its present form. By this time, the domelike structure of Spindletop had been definitely proved, and Harris,[5] on paleontological grounds, had determined a considerable uplift at Sour Lake.

[1] Robert T. Hill, communication to *Times-Democrat*, May 29, 1901. Requoted from Harris, "Oil in Louisiana," *op. cit.*

[2] "The Coast Prairie of Texas," *Science*, N.S., Vol. 14 (1901), pp. 326–28.

[3] "The Beaumont Oil Field with Notes on the Other Oil Fields of the Texas Region," *Jour. of the Franklin Institute*, Vol. 154, pp. 273–74. Philadelphia, 1902.

[4] C. W. Hayes, "Some Facts and Theories Bearing on the Accumulation of Petroleum," abstract in *Science*, N.S., Vol. 16 (1902), p. 1028.

[5] G. D. Harris, "The Geology of the Mississippi Embayment," *Geol. Surv. of Louisiana, Report of 1902*, pp. 25 ff.

Coste,[1] in 1903, advanced the theory that salt domes are the result of "volcanic emanations bringing the water, salt, sulphur, oil, and gas from the interior in the state of vapors and gases, which condensed more or less near the surface, etc." He regarded the domes and salt masses as "the dying distant echo of that tremendous volcanic energy which, a little farther south, in Mexico, Central America and in the islands and along the southern coast of the Caribbean Sea, is to this day so powerfully active."

Hayes and Kennedy[2] had made a study of the Texas-Louisiana plain just after the completion of the Spindletop well in 1901. Their report, by far the most complete regarding salt domes which had yet been published, included a geological map of the area by Kennedy, a map of the coastal oil pools and prospects, indicating a northeast-southwest alignment, and noted the parallelism of this alignment with the Balcones fault. They regarded the domes as domal or anticlinal structures but as of a type wholly different from Appalachian structures, concluding that they "could scarcely have been produced by horizontal compression." They agree with the Harris assumption of an anticline at Spindletop, but state that it was of post-Eocene rather than Cretaceous age. While they state that "the mode of accumulation of the enormous masses of rock salt which occur in the Louisiana Salt Islands, in Damon Mound, in High Island, and also in Spindletop, has never been satisfactorily explained," they quote Hill's theory of origin, noting that it presents some serious difficulties, and conclude that it may be necessary "to refer their origin to supersaturated solutions coming through fissures opened along a fault line." In noting the alignment of the domes, they state that there has been "movement along these lines, including both flexing and faulting from as far back as Miocene into the present."

Hager, in 1904, presented an able paper summarizing the existing knowledge regarding the southern salt domes and proposed, in greater detail, a theory somewhat similar to that offered by Coste. Hager's theory is essentially as follows:

[1] E. Coste, "The Volcanic Origin of Natural Gas and Petroleum," *Canad. Min. Inst. Jour.*, Vol. 6 (1904), pp. 73–123.

[2] C. W. Hayes and W. Kennedy, "Oil Fields of the Texas-Louisiana Gulf Coastal Plain," *U. S. Geol. Surv. Bull. 212*, 1903.

By contact with the molten intrusives, vast quantities of gas were generated from the reduction of metallic sulphides and the distillation of lignites and organic substances. These gases, accompanied by steam under tremendous pressure, forced their way to the surface through the unconsolidated sands and clays of the overlying Tertiary material, perhaps giving rise to mud volcanoes, such as occur in many of the world's great oil fields at the present day. Heated waters from great depths found vent along the same channels, carrying in solution carbonates of lime and magnesium, gypsum and salt. By ebullition and evaporation these solutions became concentrated until, saturation resulting, precipitation commenced, forming the necklike masses of salt, gypsum and dolomite now encountered. With the cooling of the intrusive masses and the choking of the vents, the process practically ceased. A period of subsidence followed, during which the Coastal Quaternary beds, which at present cap the mounds, were laid down, followed by a secondary movement along the old lines of weakness, resulting in the present elevation of the mounds above the surrounding prairie.[1]

Hager admits that the weakness of his hypothesis lies in "the assumption of intrusives concerning the existence of which we have no evidence whatsoever," but finds some support for it in the occurrence of intrusive rocks and the upward displacement by them of overlying strata in the Austin, Texas, area as well as in the common occurrence of some form of vulcanism in most of the world's Tertiary oil fields.[2]

Fenneman studied the coastal domes in 1904 and in the preliminary statement of his work concludes with regard to their origin as follows:

The mounds of the surface plainly owe their existence to some force exerted from beneath upward. It is inconceivable that any lateral pressure in these uncompacted Coastal Plain deposits should have resulted in approximately circular hills rising above the dead flat. It is too early to frame an exact hypothesis as to the nature of that force exerted from beneath, but indications in the field strongly suggest some association with an expansive force accompanying the crystallization of the minerals characteristic of such mounds.[3]

[1] Lee Hager, "The Mounds of the Southern Oil Fields," *Eng. and Min. Jour.*, Vol. 78 (1904), pp. 137–39, 180–83.

[2] From his numerous citations of the occurrence of mud volcanoes in various oil fields, one must conclude that Hager regarded them as true volcanic phenomena.

[3] N. M. Fenneman, "Oil Fields of the Texas-Louisiana Gulf Coast," *U. S. Geol. Surv. Bull. 260* (1905), pp. 459–67; "Oil Fields of the Texas-Louisiana Gulf Coastal Plain," *U. S. Geol. Surv. Bull. 282*, 1906.

This theory is interesting because it is apparently the first appeal to the force of growing crystals to explain the uplift of the domes.

Veatch, in 1906, after describing the igneous intrusions of southern Arkansas, concluded with regard to the origin of the salt domes of northern Louisiana and eastern Texas as follows:

> Whether the forces producing these unique domes were in any way associated with those producing the intrusions just mentioned it is as yet impossible to say; but the irregularity of their distribution, the great symmetry of all the domes which have been carefully studied, the difficulty of explaining this symmetry by any manner of folding not associated with igneous intrusions, and the suggestion which this symmetry carries of force applied at one point from below, just as a sharp-pointed little dome might be formed in a sheet of dough by pushing upward with a blunt pencil, indicate similar igneous intrusions beneath these great thicknesses of relatively plastic, recently deposited cretaceous sediments as the cause of these domes.[1]

This conclusion, so similar to that previously put forward by Hager, was arrived at independently by Veatch, who had not yet become acquainted with Hager's theory.

Harris, in 1907, first announced his theory of dome uplift by the force exerted by growing salt crystals:

> The longer we study these peculiar structures the more convinced are we that although they may be located along lines of weakness, faults, or fractured anticlines, they are not to any great extent due to tangential, mountain-making forces, nor to volcanic upheavals, nor igneous plugs, as has recently been suggested, but to the slowly-acting, little understood, concretion-forming forces as well as the power of crystallization. Hot salines or calcareous solutions, coming from earlier Mesozoic or later Paleozoic beds beneath, rising perhaps by hydrostatic pressure alone, may very readily, upon reaching a level where the pressure is somewhat relieved and the temperature decreased, deposit some of their mineral contents.[2]

He notes, in support of his theory, that calcareous concretions seem to increase in size, bending adjacent shale beds upward or downward with irresistible force until the calcareous material within their reach is exhausted. As against theories of volcanic origin, he further notes that igneous plugs and dykes usually cause great

[1] A. C. Veatch, "Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas," *U. S. Geol. Surv. Prof. Paper 46* (1906), p. 29.

[2] G. D. Harris, "Notes on the Geology of the Winnfield Sheet," *Geol. Surv. of Louisiana, Report of 1907*, Bull. 5. Baton Rouge, 1907.

irregularities in the earth's magnetic field, and that the area of the Winnfield sheet, which contains a number of domes, shows irregularities entirely too slight to indicate igneous activity in the region. In support of this contention, he later cited[1] the fact that the nearby volcanic rocks in Arkansas are magnetic.

In his subsequent writing, Harris[2] restated and elaborated his theory which, in view of his careful and detailed presentation, the lack of a more plausible theory, and the position as an authority which his intimate knowledge of the American domes[3] gave him, received widespread and almost general acceptance. The most complete statements of this theory are to be found in the *Economic Geology* article and in *Bulletin No. 7* of the *Louisiana Report*. The theory is essentially as follows:

> Artesian waters, which had entered outcropping formations north of the general salt dome areas, having descended to great depths along pervious beds, becoming heated by the high earth temperatures existing at such depths, and taking into solution salts encountered in the Palaeozoic and Mesozoic formations, rose under hydrostatic pressure at points of weakness, occurring mainly at the crossing of faults in the pre-Tertiary formations. Deposition of salt by the cooling of this hot saline solution resulted in the formation of a slender pencil-like cone of rock salt. The forces exerted by the power of the growing crystals of salt, especially at the bottom of this salt cone, resulted in the cone being pushed continuously upward as long as deposition continued, the cone being beheaded by solution as it reached the zone of circulating underground fresh waters. Overlying sedimentary rocks were lifted and contiguous rocks tilted by the upthrust of the salt cone.

Harris evidently considered that the cap rock and associated minor minerals were deposited from other solutions after the salt

[1] "Magnetic Rocks," *Science*, N.S., Vol. 29 (1909), p. 384.

[2] G. D. Harris, "The Salt Domes of Louisiana and Texas," *ibid.* (1908), pp. 347–48; "Rock Salt," *Geol. Surv. of Louisiana, Report of 1907*, Bull. 7. Baton Rouge, 1908; "The Geological Occurrence of Rock Salt in Louisiana and East Texas," *Econ. Geol.*, Vol. 4 (1909), pp. 12–34; "Oil and Gas in Louisiana with a Brief Summary of Their Occurrence in Adjacent States," *U. S. Geol. Surv. Bull. 429*, 1910; "Immense Salt Concretions," *Popular Science Monthly*, Vol. 82 (1913), pp. 187–91.

[3] Harris' Bull. 7 of the *Louisiana Geological Survey Report* and Bull. 429 of the *United States Geological Survey* are still the most complete general descriptions of American salt domes available to the student, notwithstanding the fact that in the fifteen years since their publication our knowledge of these interesting structures has increased greatly.

solution had been cut off. He cites the work of Day and Becker[1] in support of his theory of crystal force. This paper states that the power of growing crystals (in general) may be assumed to be of the same order of magnitude as the crushing strength of the crystals themselves. Harris subjected a 4-inch cube of rock salt to a pressure of 50,000 pounds, without even cracking it, and concludes that growing salt crystals could "lift up 3,000, 4,000, and even 5,000 feet of such incoherent strata" as the Quaternary clays and sands.

Coste, in 1909, elaborated his former theory of volcanic origin, noting:

> In the Mexican oil fields the volcanic action has been a little more intense and instead of only the hot gases, vapors and waters piercing up more or less through the horizontal strata to form the salines, as in Texas and Louisiana, we see the volcanic lava cones themselves piercing up boldly through the plains. There is no doubt that these lava cores in Mexico surrounded with petroleum and other solfataric emanations are one and the same volcanic phenomenon as the vertical chimneys of salts, hot waters and hot petroleums of the Texas-Louisiana salines.[2]

Campbell,[3] in 1911, reviewed theories regarding the Texas domes. He concludes that the best hypothesis put forward regarding origin is that of Harris, but believes that Hager's volcanic hypothesis had derived considerable support from the discovery of oil in the vicinity of igneous plugs in Mexico.

Clapp,[4] in 1912, reviewed the salt-dome structures. He does not arrive at a definite conclusion as to origin, merely noting that the Harris theory is the one most commonly accepted and that Hager's theory "would seem to be supported by the existence of volcanic plugs in the Coastal Plain of Mexico accompanied by many of the Texas phenomena."

[1] A. L. Day and G. F. Becker, "On the Linear Force of Growing Crystals," *Wash. Acad. Sci., Proc.*, Vol. 7 (1904), pp. 283–88.

[2] Eugene Coste, "Petroleum and Coals," *Jour. Can. Min. Inst.*, Vol. 12 (1909), p. 290.

[3] Marius R. Campbell, "Historical Review of Theories Advanced by American Geologists to Account for the Origin and Accumulation of Oil," *Econ. Geol.*, Vol. 6 (1911), pp. 363–95.

[4] G. F. Clapp, "The Occurrence of Oil and Gas Deposits Associated with Quaqua-versal Structure," *ibid.*, Vol. 7 (1912), pp. 364–81.

Turrentine,[1] in 1913, after considering the Hill-Harris and Hager theories as possible, concludes that the formation of salt domes as the result of great pressure on plastic salt masses of the inclosing, less plastic rocks is a theory whose assumptions are less violent. He notes that the plasticity of salt masses is a known and not an assumed quantity, and considers:

> If at ordinary temperatures this quantity is insufficient to account for the fluidity which has been exhibited by the masses comprising the salt domes, it may be easily assumed that the salt was warmed to its melting-point by volcanic heat.

He further considers:

> The formation of salt domes, then, would be the result of ascending columns of fused sodium chloride. Recrystallization would occur when the surface had been approached, being induced by lower temperature or lower pressure, or both. Crystal formation, as suggested by Harris, may have added its forces to the pressure of the ascending molten mass.

Cowles,[2] in 1913, suggested osmotic pressure of diffusing fresh water above salt water under a hydrostatic head as a cause of "bursting upward" where resistance is least to form a salt dome.

Lucas,[3] in 1914, states that he "has long held the opinion that igneous rock in the form of laccoliths, batholiths, or sills may underlie the salt domes of Louisiana, Texas, and elsewhere." He further states that he has "held the opinion, with Mr. Coste, that emanations of gas through these domes constitutes evidences of volcanic origin," but that "the salt was not deposited by evaporation, but must have been deposited by saline waters ascending from great depths."

In another paper reaffirming his theory of volcanic origin of oil, Coste continues with regard to salt domes:

> That these are solfataric volcanic emanations is made plain by the occurrences of oil a little farther south, along the same coastal plain, in Mexico. There one can actually observe numerous volcanic necks of olivine basalt, scattered at

[1] J. W. Turrentine, "The Occurrence of Potassium Salts in the Salines of the United States," *U. S. Dept. of Agriculture, Bureau of Soils, Bull. 94.* Washington, 1913.

[2] A. H. Cowles, *Min. & Met. Soc. Amer. Bull. 57*, Vol. 6 (1913), p. 44.

[3] A. F. Lucas, "Discussion of Hoefer's Paper on 'The Origin of Petroleum,'" *Trans. Amer. Inst. Min. Eng.*, Vol. 48 (1915), p. 494.

wide intervals, and also distributed along fault lines similar to the lines connecting the salines of Texas and Louisiana.[1]

Washburne,[2] in 1914, seems to favor the theory of volcanic origin, regarding the salt as having been precipitated from saturated brines of sedimentary origin by hydrochloric acid from igneous intrusions.

Siebenthal,[3] in 1915, after reviewing current theories of salt-dome origin, concludes in favor of deposition from solution from alkaline-saline, sulphureted waters of artesian origin and that "the very close similarity of the deposits and the artesian waters of the saline domes to those of the Joplin region indicates similarity of origin." His consideration of the domes is confined chiefly to Belle Isle, where Veatch[4] had noted the presence of fairly large masses of galena, sphalarite, pyrite, chalcopyrite, and barite in clay strata over the salt.

Norton,[5] in 1915, suggested still another somewhat complex variation of the volcanic and deposition from solution theories. He regarded the initiation of the domes as resulting from "the intrusion of molten rocks into the underlying Paleozoic sediments along lines of structural weakness." He postulated the building up of a pipe of calcareous sinter and gypsum from hot-spring deposits—contemporaneously and balanced with continued sinking of the coast and deposition of sediments, the dissolving of the lower part of this sinter pipe and deposition of salt from solution in the space formerly occupied by it, and the covering of the whole, in the case of the coastal domes, by 1,000 feet of later Tertiary sediments.

Dumble[6] regards this theory as one "which seems a step in advance of former ones," but Harris, in discussing the theory, points

[1] E. Coste, "Rock Disturbances Theory of Petroleum Emanations vs. the Anticlinal or Structural Theory of Petroleum Accumulations," *ibid.*, p. 510.

[2] C. W. Washburne, "Chloride in Oil-Field Waters," *ibid.*, pp. 687–94.

[3] C. E. Siebenthal, "Origin of the Zinc and Lead Deposits of the Joplin Region," *U. S. Geol. Surv. Bull. 606* (1915), pp. 208–11.

[4] "The Five Islands, Louisiana," *op. cit.*

[5] E. G. Norton, "The Origin of the Louisiana and East Texas Salines," *Trans. Amer. Inst. Min. Eng.*, Vol. 48 (1916), pp. 502–11.

[6] E. T. Dumble, "The Occurrence of Petroleum in Eastern Mexico as Contrasted with Those in Texas and Louisiana," *ibid.*, Vol. 52 (1916), p. 263.

out the lack of evidence of volcanic activity, in fact, the evidence against such activity, and particularly the entire neglect of the theory to suggest any satisfactory explanation of the dome structure which is so marked a characteristic of this form of salt deposit.

Lucas,[1] in 1917, after vaguely invoking volcanic origin, merely states: "As to the manner in which the salt with its gas and oil inclusions attained its present position, at a depth of 1,500 to 3,171 feet—whether in solution or as semi-plastic mass, has never been satisfactorily explained."

Kennedy,[2] the dean of American salt-dome students, in 1917 suggested that the salt masses were formed by precipitation of salt and calcareous minerals from thermal springs in small depressions or ponds along lines of weakness corresponding to the present dome alignment, on a gradually sinking coast, and that the source of the salt was Tertiary and younger rather than Paleozoic rocks. This theory differs but slightly from that of Norton and seems to be open to similar criticism.

Shaw,[3] in discussing the various possible origins, presents no conclusions, but notes that in his study of the mud lumps of the Mississippi Delta, the question arose of whether salt domes might not be due to isostatic forces, to some gravity-induced solid or semi-solid flowage.

Hopkins,[4] in 1917, expressed the view that the structural conditions found at salt domes are such as "are most commonly produced by igneous intrusion, of which no direct evidence has been found in any of the numerous salt domes of the Gulf Coast," and that it is quite probable that the forces forming the domes "were connected with igneous activity."

Deussen,[5] in 1918, stated that he was "inclined somewhat to the

[1] A. F. Lucas, "A Review of the Exploration at Belle Isle, Louisiana," *ibid.*, Vol. 57 (1918), pp. 1034–53.

[2] William Kennedy, "Coastal Salt Domes," *Southwestern Assoc. Pet. Geol. Bull.*, Vol. 1 (1917), pp. 34–59.

[3] E. W. Shaw, "Possibility of Using Gravity Anomalies in the Search for Salt-Dome Oil and Gas Pools," *Science*, N.S., Vol. 46 (1917), pp. 553–56.

[4] Oliver B. Hopkins, "The Palestine Salt Dome, Anderson County, Texas," *U. S. Geol. Surv. Bull. 661G* (1917), p. 264.

[5] Alexander Deussen, "Review of Development in the Gulf Coast Country in 1917," *Amer. Assoc. Pet. Geol. Bull.*, Vol. 2 (1918), p. 37.

belief that the dome formation is originally initiated by volcanic action."

Matteson,[1] in 1918, reviewed the principal theories of dome origin, stating objections to all of them, and concluding that the Harris theory "is one of the most ingenious that has been propounded, conforms with the field evidence, is plausible, and has been generally accepted by geologists familiar with the Gulf Coast region," and that "it forms an excellent, reliable working hypothesis in conducting field operations." This paper was more notable for the discussion which it aroused than for any original contribution to the subject. It provoked Lucas to reaffirm his adherence to the theories of Hager and Coste; G. Sherburne Rogers attacked the deposition from solution theories on grounds of quantitative sufficiency and guardedly advanced the theory of salt intrusion; Shaw objected to the theory of isostatic flowage on the grounds that the coastal plain sediments were lighter than salt. Coste restated his volcanic theory as follows: "I not only believe in the volcanic rocks under these domes but believe that the salt, the sulphur, and the hydrocarbon emanations are also absolute, direct emanations from below." Kirby Thomas advanced a variation of the deposition from solution theory. Washburne supported Roger's objections to the Harris theories and preference for the theory of salt intrusion. Anson G. Betts proposed a very improbable theory postulating the dissection of a salt bed by erosion, the burial of the buttelike outliers by sediments and the subsequent settling of the sediments. Kennedy defended the deposition from solution theories against Rogers' attack and suggested the Tertiary and Cretaceous as a source of the salt, rather than the Permian, objecting that the Permian was probably not present under the salt-dome region.

In this discussion, Rogers noted "the discovery, during the past summer, of volcanic ash in the sediment around one or two of the domes, of a rock resembling a porphyry in a well at Damon Mound; and of an undoubted igneous plug about fifty miles north of the salt-dome belt." Unfortunately, in the untimely death of Rogers we lost one our most interested and advancing students of this problem. It

[1] W. G. Matteson, "Principles and Problems of Oil Prospecting in the Gulf Coast Country," *A.I.M.E.*, Vol. 59 (1918), pp. 435–91.

was impossible to get definite information on these reported occurrences of igneous rock. In his subsequent paper on intrusive origin, Rogers repeats his note on volcanic ash and on the igneous plug, but makes no further reference to the "rock resembling porphyry in a well at Damon Mound." The occurrence of volcanic ash is of no particular significance, and Pratt,[1] after an investigation of this report, concludes that the "igneous plug" is porcelanite from Grimes or Brazos County; that the "porphyry" is sedimentary rock fused by the frictional heat of core drilling, and that "it is likewise probably true that no rock of igneous character other than fused core-barrel samples has been obtained from Gulf Coast wells." This is doubtless the explanation of these references, but it is odd that Rogers, who had studied and published on porcelanite in the northwest, where it is of such common occurrence, should have mistaken these Texas outcrops.

THIRD PERIOD (1916–25); STRUCTURAL OR SALT-FLOWAGE THEORIES

The theory of formation of American salt domes through the flowage of salt under pressure, and adaptation, so to speak, of the most generally accepted European theory of salt-structure origin, was foreshadowed by Lucas[2] in his statement that the salt of Jefferson Island seems to have been folded and contorted while still in a plastic condition; by Turrentine's conclusions regarding origin; by Shaw[3] in his query as to whether salt domes might not be due to isostatic forces, to some gravity-induced solid or semi-solid flowage; by Hahn's[4] description of European deposits; and by the experimental work of Adams[5] and Johnston and Adams[6] on the flowage of salt under pressure.

[1] Wallace E. Pratt, "A Note on the Supposed Evidence of the Volcanic Origin of Gulf Coast Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5 (1921) pp. 91–94.

[2] *Op. cit.* [3] *Op. cit.*

[4] F. F. Hahn, "The Form of Salt Deposits," *Econ. Geol.*, Vol. 7 (1912), pp. 120–35.

[5] Frank D. Adams, "An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks, Employing the Process Suggested by Professor Kick," *Jour. Geol.*, Vol. 18 (1910), p. 489.

[6] John Johnston and L. N. Adams, "On the Effect of High Pressures on the Physical and Chemical Behavior of Solids," *Amer. Jour. Sci.*, Vol. 35 (4th series, 1913), p. 251.

The theory was put forward seriously for American domes in 1917–18 by Van der Gracht, the writer, Dumble, and G. Sherburne Rogers, and has been most favorably received.

Van der Gracht, one of the first of European geologists to become intimately acquainted with our salt-dome problems, after discussing the German and Roumanian salt structures and their similarity with those of the Gulf Coast, concluded:

> I consider these saline plugs as having been *pushed upwards* by orogenic pressure, and not by recrystallization forces inherent in the rock salt. It is my firm belief that the intense lateral pressure has caused the rock salt to behave as a plastic mass and has squeezed it upwards not unlike a volcanic neck, wherever the overlying strata afforded a weak spot inviting passage.[1]

He regarded recrystallization as taking place but as an effect and not as a cause.

The writer, in 1918, reviewed the theory of volcanic origin with special reference to the suggested analogy with the oil fields of the Tampico-Tuxpam region, and concluded:

> The lack of evidence of any considerable volcanic activity in the salt-dome regions of Texas and Louisiana or in the salt-dome region of the Isthmus of Tehuantepec, Mexico, as well as the entire absence of any salt masses of the nucleus type in the Tampico-Tuxpam region, Mexico, a region of considerable volcanic activity, would seem to argue most strongly against the acceptance of the volcanic theory of salt dome origin. . . . .
>
> Finally, since the attractiveness of the theory of volcanic origin of salt dome lies in the similarity of structural effect produced by the intrusion of the salt in many domes to that produced by the intrusion of the igneous rock of a volcanic neck or plug, it follows that we are interested in the conditions and forces which caused the salt to act in a manner so like to that of an igneous magma. . . . .
>
> Rather, the structure of the domes would seem to make it evident that the salt itself must have flowed. Such flowage was most likely due to great pressure exerted upon buried salt masses by the weight of overlying rocks, and at considerable temperatures and probably accompanied, as has been suggested by van der Gracht, by recrystallization of the salt.[2]

[1] W. A. I. M. von Waterschoot Van der Gracht, "The Saline Domes of Northwestern Europe," *Southwestern Assoc. Pet. Geol.* Vol. 1 (1917), pp. 85–92.

[2] E. DeGolyer, "The Theory of Volcanic Origin of Salt Domes," *A.I.M.E.*, Vol. 61 (1919), pp. 456–77.

In the discussion of this paper, J. A. Udden stated that neither this theory nor the volcanic theory explained the cap rock and held that, whatever theory might be developed, the Hill-Harris theory, which he evidently regarded as satisfactorily explaining the cap rock, was not likely to be entirely replaced.

Dumble, in his discussion of the same paper, gave an extended description of the domes, and put forward a theory which is essentially an intrusion theory but also, by definition, a volcanic theory and one which seems to the writer very interesting and one of the most plausible theories proposed to meet our own special problem. His conclusions are as follows:

> The character and structure of the domes show conclusively that they are the result of orogenic action and that this activity has been manifested at different times and in different degrees.
>
> The interior domes and the Sabine Peninsula were begun by crustal movements at the end of the Upper Cretaceous, and were involved in later movements at the end of the Lower Eocene and during the Claiborne or Middle Eocene, resulting in total elevations of 2,500 feet [762 m.] or more above their normal horizon.
>
> Similarly, the coastal domes were elevated by orogenic forces acting after the deposition of the Lafayette and prior to that of the Port Hudson clays. The elevations in this case are fully as great as in those of the interior domes, as is proved by drilling. In the case of Damon Mound, the elevation does not appear to have entirely ceased, since the San Bernard River, flowing on its western side, seems to be still cutting its canyon where it crosses it, although to the north and south its banks are low and flat. The movements are most probably the result of isostasy.
>
> According to the writer's point of view, the question of vulcanicity cannot enter into the origin of the materials of which the domes are composed, since, although salt may be formed by volcanic emanations, we have here no need to invoke such a theory of its origin, since a more natural one is probable. Neither is it believed to be the actual dome producer, but rather an accompanying factor or feature of the forces which caused them.
>
> Both salt and anhydrite become liquid at far lower temperatures than any lava, and existing in considerable bodies, as they probably did here, could be readily forced into any opening caused by flexures or faulting of the crust above them more easily than a plug of basalt. Apparently this is what has occurred, and since the term vulcanism is used by Chamberlin and Salisbury "to embrace not only volcanic phenomena in the narrower sense, but all outward forcing of molten material, whether strictly extrusive or merely ascensive," it is thought to

cover the phenomena of the intrusive salt, gypsum, and anhydrite stocks in these domes, as fully as if the stocks were basalt or other rock material.

Rogers,[1] shortly afterward, published an exposition of the European theory and suggested the application of the theory of dome formation through salt flowage to the American domes. He described the development of the theory in Europe, the general outlines of the nature of European salt structures, and the plasticity of salt, and concluded: "The writer is inclined to believe that the Gulf Coast salt domes, like those in northwestern Europe and Roumania, are offshoots of bedded salt deposits, formed and forced upward by pressure in a semi-plastic condition." He argues Permian deposits of bedded salt as the most likely source of the salt and pressure by lateral thrusting of deeply buried rocks as the most plausible source of pressure, pressure occasioned by igneous intrusion (batholithic) as possible, and by isostatic adjustment as improbable. He argues that cap rock may have been formed by precipitation from solution by ground waters, and that we are hardly justified as yet in accepting the German view of regarding the cap rock as a residue left from the dissolving of the salt dome. Rogers also quotes Mrazec, notable for his studies of Roumanian salt structures and who had recently visited the Gulf Coast region, as agreeing to the intrusive origin of the domes. He quotes Becker, upon whose work on the force exerted by growing crystals Harris bases his theory of dome uplift through the power of crystallization, as follows:

> I do not for a moment believe that the linear force of growing crystals has caused intrusion of salt plugs or doming of the sediments. It may to some extent have modified the action on the walls and have aided in causing distortions within the mass. Recrystallization of the salt *in situ* would obliterate the strains in such crystals.

In a discussion of this paper, the writer[2] argued for the formation of the cap rock by deposition from solution after the salt mass had been formed and, citing Cameron's experiments upon the solubility of gypsum in saline solutions, suggested that the salt might have

[1] G. Sherburne Rogers, "Intrusive Origin of the Gulf Coast Salt Domes," *Econ. Geol.*, Vol. 13 (1918), pp. 447–85.

[2] E. DeGolyer, "Origin of the Cap Rock of the Gulf Coast Salt Domes," *ibid.*, pp. 616–20.

been the agent which precipitated gypsum or anhydrite from solution.

Lucas,[1] in 1918, again advocated the volcanic origin of the salt domes and, by the publication of a hypothetical section, rather cleared up his previously expressed ideas. His section shows the salt dome above a laccolith and separated from it by arched beds of Cretaceous and younger rocks.

The writer,[2] in 1919, suggested that the formation of the interior group of salt domes was of comparatively recent date and might not yet be complete. He questioned whether a salt dome whose formation can be established beyond doubt as having occurred in pre-Tertiary time can be cited, and suggests that theories of origin implying long life or great age for a dome should be looked upon with suspicion.

Powers,[3] in 1920, regarded the tectonic theory of dome origin as acceptable, granted the existence of a source bed of salt.

Lucas, in 1920, presented his last statement as follows:

> According to my present views, the salt domes occur on lines of structural weakness that are responsible for the location of the plugs of salt, whether the latter originated from solutions, as I have been inclined to believe, or are products of extrusion from the deeply buried older formations, whose thrusting or faulting is responsible for the "pre-existing weakness" already mentioned. . . . .
>
> Further movement along the line of weakness may well have occurred subsequent to the original dislocation and possible saline extrusion, and it is along fractures thus produced in the salt plugs that the sulphur and other caprock materials have been brought to the surface.[4]

White,[5] in 1920, referred to the "pressure theory of the origin of the salt plugs" as one "which seems to demand acceptance."

[1] Anthony F. Lucas, "Possible Existence of Deep-seated Oil Deposits on Gulf Coast," *A.I.M.E.*, Vol. 61 (1919), pp. 501–19.

[2] E. DeGolyer, "The West Point, Texas, Salt Dome, Freestone County," *Jour. Geol.*, Vol. 27 (1919), pp. 647–63.

[3] Sidney Powers, "The Butler Salt Dome, Freestone County, Texas," *Amer. Jour. Sci.*, Vol. 49 (1920), pp. 127–42.

[4] A. F. Lucas, "Urgency for Deeper Drilling on the Gulf Coast," *Trans. Amer. Inst. Min. & Met. Eng. Preprint No. 100.4*, 1920.

[5] David White, "Genetic Problems Affecting Search for New Oil Regions," *ibid.*, Vol. 65 (1920), pp. 176–98.

Mills and Wells[1] in 1919, advanced the theory that among the possible causes of deposition of salt-dome materials from solution is the evaporation of water from solution by expanding gases. Accepting the intrusion theory of dome origin as possible, they advance the effect of evaporation as having played a large part in the formation of the domes, but do not claim that the theory fully explains their formation.

Washburne,[2] in 1920, attacked the Mills and Wells hypothesis of precipitation from solution by evaporation as an explanation of origin. The argument against this theory specifically was largely on the grounds of quantitative insufficiency. Deposition from solution theories generally were held improbable, because of dilution of the hypothetical rising salt solution by meteoric waters, particularly artesian waters, and consequently salt would not be deposited. Washburne regards the theory of intrusive origin as more acceptable. He pointed out limitations of the writer's suggestion of cap-rock deposition from solution by increased salinity.

Matteson,[3] in 1921, attacked the theory of intrusive origin as set forth by Rogers and proposed a theory of "secondary intrusion" which postulated the deposition of salt masses and limestone from solution, largely through gas evaporation of the water; initial movement and uplift through the force of crystallization, and increase in volume by the conversion of limestone into gypsum; and secondary intrusion by salt flowage resulting from lateral thrust and compression. This theory seems to be a merger of most previously expressed theories and in sum total inherited more of their weakness than of their strength. Nor was its author happier in his attempt to discredit the very actual analogies between European and American salt structures by a catalogue of their differences and neglect of their similarity.[4]

[1] R. van A. Mills and R. C. Wells, "Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas," *U. S. Geol. Surv. Bull. 693*, 1919.

[2] C. W. Washburne, "Oil-Field Brines," *Trans. Amer. Inst. Min. & Met. Eng.*, Vol. 65 (1921), pp. 269–94.

[3] W. G. Matteson, "Secondary Intrusive Origin of Gulf Coastal Plain Salt Domes," *ibid.*, pp. 295–334.

[4] No one can read the Washburne and Matteson papers and their discussions without delight at the various solemn warnings against the sins of speculation in dealing

Barton,[1] in 1921, gave favorable consideration to the theory of intrusive origin of the salt at West Columbia, explaining in considerable detail the probable similarities and differences between the intrusion of a salt plug and of a volcanic neck. He rejected, for American domes, the European theory that cap rock is a residual deposit resultant upon the solution of an impure salt mass on the grounds that the salt of the American domes is extremely pure and that the cap rock does not always cling closely to the surface of the salt mass as would residual material.

Cheney,[2] in 1922, advanced a theory that the Texas interior domes, except Grand Saline, occur on the crest of an anticlinal fold parallel to the Balcones fault and Mexia anticline. He regarded the salt as of Middle or Lower Cretaceous age, the domes to have been formed by cross-folding and erosion in pre-Tertiary time, and the apparent vertical thickness of the salt is ascribed to close folding, and dome structure in the younger formations to continued folding. This theory was discussed by Heald,[3] who regards it as "based entirely upon assumptions, none of which can at present be verified, and some of which seriously tax the imagination and credulity," and disposes of it in some detail.

In 1923, Powers and Hopkins[4] concluded that "the deposition of salt from solution in fissures or other openings seems to be a self-limited and inadequate process to account for the domes" and in the lack of information that would suggest any other explanation "pre-

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with this subject of dome origin. The truth is that whoever touches this enticing subject within the present century, and perhaps for longer, is bound to indulge freely in speculation. The problem is so broad, the factors involved are so numerous, and the work to be done with regard to salt structures is so great that we cannot for many years to come expect to hedge our tendencies to speculate to any very narrow range by the limits of exact knowledge.

[1] D. C. Barton, "The West Columbia Oil Field, Texas," *Amer. Assoc. Pet. Geol. Bull.*, Vol. 5 (1921), pp. 212–51.

[2] Charles A. Cheney, "Salt Domes of Northeastern Texas," *Oil and Gas Jour.*, Vol. 20 (Jan. 6, 1922), No. 32, pp. 82–83.

[3] K. C. Heald, "Salt Domes of Northeastern Texas. A Review," *Amer. Assoc. Pet. Geol. Bull.*, Vol. 6 (1922), pp. 58–59.

[4] Sidney Powers and Oliver B. Hopkins, "The Brooks, Steen, and Grand Salt Domes, Smith and Van Zandt Counties, Texas," *U. S. Geol. Surv. Bull. 763* (1923), pp. 179–239.

sented the tectonic theory as best explaining the origin of the domes of Louisiana and Texas."

White, in a very recent paper, in considering the gravity anomalies observed at Damon Mound, states:

> Admitting that the salt is extruded, it would hardly be forced to overcome so great resistance except by powerful lateral thrusts, first forming an anticline, and later presumably overturning the fold before producing the fracture or tearing of the deeper consolidated strata through which the salt might press upward on lines of least resistance. Faulting or overturned buckling beneath the plug is a normal geologic probability. The movement squeezing the salt upward across thousands of feet of strata is possibly post-Miocene.[1]

Deussen,[2] in 1924, published the results of work done some years previously in southwestern Texas. He describes several salt domes but reaches no very definite conclusion regarding origin. He states, "Salt domes represent intrusions of massive saline cores into sedimentary formations," and notes that there are three main theories of origin: the volcanic, deposition from solution, and salt-flowage theories. He regards the theory of precipitation from ascending solution as "more likely" than the theory of volcanic origin.

DISCUSSION OF TYPES OF THEORIES

The problem of developing an acceptable theory to explain the origin of the salt domes of North America—of the Texas and Louisiana province—is essentially one of trying to explain, in the simplest manner possible, the formation of these peculiar structures by known and adequate geologic processes. The theory which best meets this requirement is more rational and less speculative than one which does not, and as such is entitled to at least a tentative general acceptance. The most complicated theory yet put forward, and this is saying a great deal, may be the correct one, but probabilities are strongly against it and we are here dealing with probabilities rather than possibilities.

The solution of the problem has not been possible in the past in the insufficient state of our knowledge. The probable alternative

[1] David White, "Gravity Observations from the Standpoint of the Local Geology," *Geol. Soc. Amer. Bull.*, Vol. 35 (1924), pp. 207–77.

[2] Alexander Deussen, "Geology of the Coastal Plain of Texas West of Brazos River." *U. S. Geol. Surv., Prof. Paper 126.* Washington, 1924.

hypotheses for methods of salt-dome origin have been well outlined by previous students of the problem.

The writer has no new theory to propose. The weight of the evidence which has been accumulating with increasing rapidity during the past very few years has been, however, cumulatively in favor of the sedimentary salt-flowage theory, and now with the recent discovery at Markham the writer believes that this theory has been established with a high degree of scientific probability.

The theories of dome origin already put forward fall into four general groups: (1) those regarding the domes as old outliers; (2) those regarding the salt-dome materials—the salt core and cap rock—as having been precipitated from solution; (3) those regarding the domes as of volcanic origin; and (4) those regarding the salt as a plastic or semiplastic body forced by pressure into its present position. All of the theories which seem to be worthy of serious consideration belong to one of these groups or, with variations and combinations, to two or more of them.

1. The first group of theories—those which regard the domes as old Cretaceous outliers in Tertiary seas—belong to the earliest stages of our study of salt domes. They received general acceptance in their time, but were discarded when we began to know something of dome structure, and they now no longer demand serious consideration.

2. The deposition from solution theories, first advanced by Goesmann, and in greater detail by Hill and Harris, are not acceptable in their simpler forms, since they offer no adequate explanation of the uplift of the strata overlying and contiguous to the salt. An attempt is made to remedy this deficiency by an appeal to the force supposed to be exerted by growing crystals—a modification of the theory which was suggested by Fenneman and elaborated by Harris. This modified theory has received favorable consideration and widespread acceptance, but is not acceptable to the writer. He does not believe that such immense bodies of salt—stocks averaging a mile in diameter and thousands of feet in thickness—were ever deposited from solution, nor does he believe that the ingenious appeal to force exerted by growing crystals can satisfactorily explain the tremendous forces which evidently operated in the formation of the dome.

Brines are of the commonest and most widespread occurrence, yet comparatively pure salt deposits which can be proved definitely to have been deposited from solution, except in bedded deposits, are rare indeed, and quantitatively of distinctly minor importance. Nor can it yet be established that the force exerted by crystals growing from aqueous solution, as proposed by Harris, has ever operated on a scale adequate to explain force of the magnitude operative in the formation of salt domes. Harris cites the compression of shales enveloping a calcareous concretion as evidence of the actual operation of this force as a geologic process, but as negative evidence we have any number of mineral deposits, known to have been deposited from solution and of minerals which should exert even greater forces in crystal growth than most salt, where there is lack of evidence of force of crystal growth of anything like the magnitude necessary to explain salt-dome formation. It is worthy of note that Becker, the geophysicist upon whose experimental work on the force exerted by growing crystals the Harris theory largely rests, concludes: "I do not for a moment believe that the linear force of growing crystals has caused intrusion of salt plugs or doming of the sediments." Furthermore, the mechanics of the Harris theory is weak. The formation of a salt mass of dome magnitude would have had to be a slow and relatively continuous process in order to provide enough brine to supply the salt. The writer cannot conceive of free brine circulation—the arrival of fresh brine and escape of the lean solution —in a cavity, where the salt already deposited is exerting a pressure great enough to lift thousands of feet of strata. The process would seem to be self-inhibiting long before a salt dome could have been formed. The only variations of the theory of deposition from solution which overcome this difficulty, those of Norton and Kennedy, do not explain the dome uplift.

3. The theories of volcanic origin, first proposed as a pure speculation by Thomassey and more seriously by Lee Hager and Veatch, are worthy of serious consideration, if for no other reason, because they have appealed so generally to the men most intimately acquainted with the North American salt domes. Lee Hager, Lucas, Deussen, Clapp, Veatch, Dumble, Oliver B. Hopkins, and Washburne have at one time or another expressed themselves as favorably

inclined toward a theory of volcanic origin. The writer believes that this general appeal results from the fact that structurally an igneous plug is the only geological feature known to us which even remotely resembles a salt dome, and the similarity of the two is indeed striking. He believes, however, since the salt in the one occupies the same structural position and evidently performed the same uplifting function as the igneous magma in the other, that if the problem had been more clearly thought out, we would have concerned ourselves with the conditions and forces which caused the salt to act in a manner so like to that of an igneous magma instead of appealing to volcanic origin to explain salt domes.

All theories of volcanic origin are open to the objection that there is no positive evidence of volcanic activity in the salt-dome regions of North America, an objection well recognized by proponents of the theory. The comparatively high temperatures of the oil and waters associated with the domes, as well as the high sulphur content of the oils, may be interpreted as evidence of vulcanism, but they are susceptible of other explanations and are not at all conclusive. The occurrence of oil in association with volcanic rocks in the Tampico-Tuxpam region of Mexico has been cited many times in support of this theory, but the Mexican occurrence is some hundreds of miles removed from the salt-dome region of Mexico and has no definite bearing on the matter in any way.

All of the theories of volcanic origin are open to the further very definite objection that no important salt deposits ascribable to volcanic origin are known elsewhere in the world. Surely, if salt deposits of dome magnitude are the result of volcanic action, we should find at least an occasional important salt deposit in regions of known volcanic activity which could be proved to be of volcanic origin.

The volcanic theories which suppose that the salt of the domes was deposited from solution, such as Hager's theory or, more vaguely, from "emanations," such as the theories of Coste and Lucas, are open to the same objections as the other deposition from solution theories.

Dumble's theory is a tectonic theory rather than a volcanic theory, though he evidently appeals to conditions similar to those

supposed to give rise to lava pockets[1] to bring about the plastic or liquid conditions of deeply buried salt and anhydrite and thus promote its free flowage, and he refers to this process as included within Chamberlin and Salisbury's definition of volcanic phenomena.

4. The tectonic, structural, intrusion, or salt-flowage theories of salt-structure formation were first developed by European geologists to explain the origin of the salt structures of Germany and Roumania. Its application to the American problem was suggested by Hahn and Turrentine and was seriously put forward by Van der Gracht, the writer, Dumble, and G. Sherburne Rogers.

All of these theories postulate a deeply buried bed of salt of sedimentary origin and flowage in a semiplastic state, under pressure induced by orogenetic movements, or the weight of superincumbent strata to its present position. This, briefly, is the intrusive-origin theory. The writer believes it to be the most acceptable and most rational of the theories put forward to explain the origin of salt domes. It has the very definite and, to the writer's mind, conclusive superiority over all other theories of being equally suitable as applied to salt structures in general. Granting, for the sake of argument, the claims of their proponents to the validity of theories of deposition from solution or volcanic origin, or their various combinations, as satisfactory explanations of the origin of American salt domes, they lose nine-tenths of their attractiveness if they do not break down entirely, when an attempt is made to apply them to other forms of salt structures such as the long anticlinal ridges of Germany and Mexico. This objection, to the writer's mind, is decisive, since the genetic kinship of all forms of salt structures, including salt domes, is obvious. Furthermore, the tectonic theory seems to have been established for German salt structures, where the age and source beds of the salt are known, beyond reasonable doubt.

ORIGIN OF THE NORTH AMERICAN DOMES

The writer firmly believes that the North American salt domes, i.e., the salt structures of the Texas-Louisiana province, are plugs of salt intruded into previously almost undisturbed Tertiary and Cre-

[1] See the chapter on "The Origin of Pockets of Molten Rock" in W. H. Hobbs's *Earth Evolution and Its Facial Expressions*. New York, 1921.

taceous formations from deeply buried salt structures; that these deeply buried salt structures were formed by orogenetic forces; and that the flowage of the salt in a plastic or semiplastic state from original bedded deposits was induced by compression resulting from folding.

That the salt plugs are intruded into their present position by salt flowage under pressure from below, the writer considers to be reasonably established. Salt has been shown to be plastic or semiplastic and to flow under pressure. Highly folded, or semiflow structure has been found in the salt core of every salt structure where opportunity exists for its adequate examination, so far as is known. This is true for the German, Roumanian, and Mexican salt structures and for the Cardona, Spain, salt structure, and it is true for the American salt domes. Aside from the general relationship and arrangement of the salt-dome materials and contiguous rocks, this flow structure in the salt is the most common characteristic of salt structures. The upturned contiguous sedimentary rocks, dipping away from the salt in all directions, is further evidence that the salt core is intrusive, but most striking of all is the great uplift of the rocks overlying the salt-dome material. The Woodbine sands outcrop at the surface of the Palestine, Texas, salt dome where, except for the structural disturbance arising from the formation of the dome, one would expect to find Mount Selman beds—indicating an uplift of 3,200–4,200 feet. Jurassic limestones are found at the surface of the Tonolapa structure, near Chinemeca, Vera Cruz, where, except for the structure, one would expect to find beds of Miocene or younger age, indicating an undetermined uplift, for the section is not well known, but probably of the magnitude of 10,000 feet as a minimum. Van der Gracht cites Heligoland, which he regards as a salt structure, as indicating an uplift of some 20,000 feet. Uplifts of this magnitude in very sharp and narrowly defined domes, especially in areas of otherwise little or no structural disturbances, are almost impossible to explain except as the result of salt intrusion from below.

The writer considers that the salt domes of the coastal and interior groups are of contemporaneous origin. He holds this view in the absence of contrary evidence, and because it seems quite im-

probable that two independent groups of so unusual type of phenomena as salt domes should have been formed independently so near to each other in a single geologic and geographic province such as the Cretaceous-Tertiary overlap of the Gulf Coastal plain.

Dumble has suggested a different geologic history for the domes of the interior group from those of the coastal group, and Deussen, Powers, O. B. Hopkins, Dumble, and other salt-dome students conclude for intermittent growth of the domes, their argument being based on evidence of apparent lacunae in the geologic section observed at the surface of certain of the Texas interior domes, notably Deussen's statement that the Midway is absent in the Palestine dome. The writer has never accepted this theory, holding rather that the Midway might yet be found at Palestine or that, if missing, its absence in so sharp, steeply folded, and faulted a structure could easily be due to mechanical suppression such as is of common occurrence in Roumanian and other salt structures. More recent work has resulted in the finding of Midway exposure at Keechi and Palestine.[1] This new evidence would seem to eliminate such bases as existed for the arguments cited in favor of separate histories for the two groups.

As to the mechanical progress upward of the salt core, the writer is inclined to believe that it would have been somewhat intermittent. Given a salt body acting as an extremely viscous liquid and a more or less constant pressure, upward progress of the salt core, assisted doubtless by tidal kneading and water lubrication, would be regular and gradual only so long as the material penetration was homogeneous. It can be conceived that if the salt core should encounter a sufficiently resistant bed, progress of the core would be halted until pressure enough had accumulated to enable it to break through and continue its upward growth. There is also some evidence in domes of the New Iberia, Louisiana, type, that younger and smaller salt cores may have sprung from older domes which had already reached a state of equilibrium.

This tectonic theory postulates the existence of a series of sedimentary rocks containing considerable deposits of bedded salt which

[1] Private communication from Donald C. Barton based on examination made by Barton and F. B. Plummer and paleontologic determinations by Israelsky.

must be older than the oldest rocks known to be involved in the formation of any of the domes; that is to say, Lower Cretaceous or older. It presupposes, as well, the folding of this series of rocks to a degree intense enough to form salt structures before the deposition of the oldest rocks involved in the known domes—probably before the Upper Cretaceous.

The weakness of this theory heretofore has been that we have had no knowledge of the existence of such bedded deposits of salt. The existence of the salt masses themselves is, to the writer's mind, definite evidence of the existence of such older deposits of bedded salt, but he grants that this evidence would hardly be admitted by one not already strongly convinced of the intrusive nature of the salt plugs. The recent discovery of salts containing fossil algae and potash salts in the core of the Markham salt dome, however, and the discovery of potash salts in the Mexican salt structures seem to establish the sedimentary origin of the salt beyond reasonable doubt. It may be that further examination of the algae salts will give some clue as to age. Dumble argues bedded deposits of Lower Cretaceous age as the source of the dome salt, and the finding of anhydrite and red beds in the Lower Cretaceous of northwestern Louisiana and north Texas, as well as the reputed occurrence of salt itself in the Lower Cretaceous near Ojinaga, Chihuahua, give great support to his argument. In arguing for a Lower Cretaceous source of salt he is supported by so eminent an authority as Professor Schuchert, who says:[1] "The best place to get your salt is from the Comanchean."

On the other hand, there is little evidence, in outcrop around the perimeter of the Gulf Coastal plain, that the Lower Cretaceous has suffered structural disturbances such as are postulated by this theory, or sufficient to result in the formation of salt structures. The writer would be inclined to consider the age of the salt source beds as pre-Cretaceous, but here we are in quite as great difficulties. The existence of Jurassic or Triassic rocks is entirely conjectural, and Professor Schuchert opposes the existence of any Paleozoic strata which might serve as a source of the salt, it being his opinion that the Cretaceous of the Gulf Coastal plain is underlaid directly by pre-Paleozoic metamorphics.

[1] Personal letter to the writer.

If one considers the structure of the Paleozoic rocks around the perimeter of the Cretaceous-Tertiary overlap of the Gulf Coastal plain as a tectonic frame of reference, he is struck immediately by the conformability of the well-determined, northeast-southwest alignment of the salt domes of the coastal group to the general trend of pre-Cretaceous Appalachian structure, and the almost equally marked northwest-southeast alignment, as shown in the Five Islands, to the general structural trend of the pre-Cretaceous, Arbuckle-Wichita structure. The alignment of the Texas interior domes, on the other hand, follows more nearly the trend of the Balcones fault system. This argument, vague and indefinite as it is, does not favor the theory of Cretaceous salt, but it is not definite in support of pre-Cretaceous salt structures.

We have learned much regarding structure in the Cretaceous rocks of the Gulf Coastal plain as a result of the development of the Powell, Mexia, and Luling oil fields, and the subsequent geological explorations to which they gave impetus, and it may be that at some future date we shall possess sufficient knowledge to serve as a basis for a more definite conclusion as to the source of the salt of the domes. The argument at present favors the Lower Cretaceous, though the author cannot escape the feeling that although present knowledge may support Professor Schuchert's conclusion against the existence of pre-Cretaceous sedimentary rocks, further investigations may bring about a different opinion.

The cap-rock problem, to the writer's mind, is separate and distinct from the problem of the origin of the salt core of the dome. The occurrence of salt domes without cap rock would seem to indicate the truth of this assumption.

The common occurrence of cap rock in salt domes, and even salt structures, however, makes a consideration of origin desirable to round out any acceptable theory of salt-dome origin.

Whether one accepts the theory of tectonic origin of the salt domes or not, after giving due consideration to the position of the cap rock, overlying the flat top of the salt, but in the American domes at least seldom extending down its sides, there would seem to be but three possible methods of cap-rock formation: (1) as a residuum of rocks or minerals, originally interbedded with the salt

or disseminated within it, left from the solution of the salt by circulating waters; (2) as a deposit from solution; or (3) as a formation encountered by the salt core during its intrusion from below and brought up with it.

The writer is inclined to regard the theory of residual origin, developed by European geologists to explain the cap rock of their salt structures, as the most acceptable theory to account for the cap rock of American salt domes. During the intrusion of the salt core, according to the adaptation of this theory to our particular problem, the upper end of the salt plug would have been dissolved away by circulating fresh waters as successive water-bearing strata were encountered, thus forming the flat top so characteristic of our salt plugs, and leaving a residue consisting chiefly of anhydrite, which was subsequently altered to the cap rock found at present. This theory presents no particular difficulties in Germany, the place of its origin, since considerable quantities of anhydrite are known to be interbedded in the German salt masses. The weakness of the theory as applied to American domes is that there is but little evidence of considerable quantities of anhydrite in the salt core. For the most part, salt cores from American domes show so little anhydrite that it might require the dissolving of 100 feet or more of salt core to leave a residue of 1 foot of cap rock. Occasional samples, however, show considerable amounts of anhydrite.

Chapman[1] notes that rock salt encountered in the Hockley dome shows "some anhydrite in the upper parts of the deposit."

Barton notes that the core from 2,110 feet, Fitzsimmons No. 1, Brenham salt dome, is described as "40 per cent salt—60 per cent anhydrite." He examined a core from 2,172 feet in the same well and describes it as "50 per cent salt, 50 per cent saccharoidal anhydrite, interbedded in parallel zones about 1 centimeter thick." He further describes these zones as indistinctly bounded and grading into one another. The center of the salt bands was pure, clear, and transparent salt, and that of the anhydrite zones seemed to be pure, medium-grain saccharoidal anhydrite of the characteristic salt-dome cap type.

[1] Lewis C. Chapman, "The Hockley Salt Dome," *Bull. Amer. Assoc. Pet. Geol.*, Vol. 7 (1923), pp. 297–99.

Interbedded salt and anhydrite are also of common occurrence in the Mexican salt structures, but here the anhydrite not only occurs far down on the flanks, as in the German structures, but is also interbedded with shale as well. The Mexican occurrences are of a type much more complex than elsewhere, so far as is known to the writer. It seems probable that in a salt structure such as Ixhuatlan, much of the anhydrite encountered in drilling is part of the salt core and is in no sense cap rock as we are accustomed to use the term in the United States. Much original anhydrite of this type is found in the salt cores of the German structures. True cap rock is also found in both the German and Mexican structures.

Recent drilling at Markham has also resulted in the finding of interbedded salt, shales, and anhydrite in a position far down on the flanks of the dome. The position of these materials suggests that they also may belong to the original salt core.

The limestone of the cap rock may be material encountered by the salt dome in its upward progress—plucked material, so to speak—but the writer is inclined to regard it and the gypsum as alteration products of anhydrite and to regard the sulphur, oil, and other minor minerals as secondary accumulations, deposits from circulating waters, and alteration products.

CONCLUSIONS

In presenting his conclusions, the writer cannot well brief the present paper, but prefers to give his own working hypothesis as to the origin of the salt domes of North America, i.e., the salt structures of Texas and Louisiana.

The salt and anhydrite of the salt core are believed to have been deposited originally in lagoons and embayments before Upper Cretaceous time. The sedimentary origin of the salt would seem to be definitely fixed by the discovery of fossil algae and potash in salt from the Markham dome as announced in this paper. This period of deposition cannot be fixed definitely as older than Lower Cretaceous; indeed, such scant evidence as we possess has a decided Lower Cretaceous complexion, and the authority of so eminent a geologist as Dr. Schuchert is definitely opposed to carrying the age of the salt back to an earlier date.

The salt, anhydrite, and the sediments with which they were interbedded were closely folded by orogenetic movements. Flowage of the salt under compression produced salt structures, which were probably of an anticlinal ridge type, similar to those of the Harz Mountain (Stassfurt) region of Germany. This period of folding is regarded by the writer as essential to the formation of the salt structures, and as it must have been more intense than any of the structural disturbances which have been found thus far in the Cretaceous and younger rocks of the Gulf Coastal plain, this period of folding is believed by the writer to belong to pre-Cretaceous, probably Paleozoic, time and is the basis for his inclination to regard the salt as of pre-Cretaceous age. This view is further supported by the parallelism of the salt-dome alignment to the old Appalachian folding and to the old Arbuckle-Wichita folding.

The entire area of salt structures was submerged and a blanket of some thousands of feet of strata of Cretaceous, Tertiary, and Recent age was deposited upon it. The salt cores of the structures continued to flow, and breaching the old anticlines in which they were first formed, some of the more active cores were forced upward into the almost level-lying blanket of younger rocks. In their penetration of the younger rocks, the salt masses were restricted to a conical form of almost circular plane section, the form of easiest flow and least wall friction. The younger rocks immediately over the salt cores were punched through the overlying rocks and, in instances, lifted thousands of feet. The sedimentary rocks adjacent to the salt core were tilted upward into funnel-like structures dipping away from the salt in all directions. Resistance afforded by the pierced sediments resulted in the blunting of the top of the cone—even a mushrooming as at Vinton, Anse le Butte, Keachi, and other domes. Through continual solution of the upper part of the salt core, eaten away by circulating waters, the anhydrite, originally present as disseminated granules in the salt as in the salt bands of the Five Islands, or interbedded as at Brenham and perhaps at Markham, was left as a residue which formed the cap rock. By hydration, part of the anhydrite became gypsum and some of the gypsum, in turn, by the reaction with circulating mineral waters and organic material was altered to limestone and sulphur or sulphur gases.

The petroleum and natural gas that is found on so many of the salt domes is thought to have accumulated after the formation of the dome. The effect of the dome was merely to afford a type of structure favorable for the accumulation of oil and gas, and the accumulation took place by the normal processes by which it takes in the more ordinary oil and gas structures, with the exception, however, that upward migration across stratification was much more important than in the ordinary types of oil and gas structures.

DISCUSSION

C. S. SCHUCHERT: I have listened with a great deal of interest to what has been said in regard to the salt-dome structures and the various theories seeking to explain the origin of the coastal salt domes. If their origin is to be explained as due to tectonic or volcanic causes, and the salt of the domes is deep-seated bedded salt that has risen into domal structures, then historical geology and times of crustal movements enter into the solution of this most vexed problem. While I have nothing of a definite nature to offer, I want to call attention to several probabilities of a paleogeographic and historic nature that may help toward solving how and when these domes originated.

Because the salt of the domes in North Germany is of Permian origin, there is a widespread feeling among petroleum geologists that there are also Permian formations with salt beneath the coastal domes. For this conclusion I do not find in the paleogeography of North America the slightest evidence. The lay of the Paleozoic formations of the mid-continent oil fields all point to an eastern borderland (Llanoria) throughout the eastern part of Texas, western Louisiana (Sabine uplift), and southern Arkansas during this era. This was the land that furnished the tremendous thicknesses of Pennsylvanian sediments in Arkansas, Oklahoma, and Texas. It appears that within the United States, Llanoria remained land until at least the close of Comanchian time. This is indicated by the paleogeographic maps in the second edition of my *Historical Geology*. In my studies I see no possibility of marine salts in the region of Llanoria earlier than Comanchian time, and now that red strata of Lower Cretaceous age are known in northeastern Texas, and anhydrite in Louisiana, why not beds of salt of Cretaceous time?

Borderlands are periodically rising masses and are more apt to be studded with volcanoes that the areas of epeiric seas. On the other hand, it is well known that during Upper Cretaceous time the seas of Texas had active volcanoes, and why not also the borderland Llanoria? Furthermore, as Appalachia was repeatedly raised vertically during the Mesozoic, why should not Llanoria during the early Cenozoic have been repeatedly faulted, and the blocks let down variously into the developing Gulf of Mexico? The latter appears to have been started in Mexico during late Jurassic time, in Texas during the Lower Cre-

taceous, and certainly in the western gulf area toward the close of the Mesozoic era.

On the basis of the foraminiferal studies of the Houston paleontologists, it is now known that some of the coastal salt domes came in after Jackson time, that the earlier Oligocene marine strata pinch out against these domes, and that the later strata of the same series completely crossed them. Certain domes appear to be of younger origin, and it is thought by some geologists that yet other domes are still in movement. It occurs to me that there may be many salt domes of early Cenozoic origin that lie buried beneath the very thick Miocene strata.

I therefore offer the hypothesis that the salt domes are due to faulting of old Llanoria during Cenozoic time, and chiefly previous to the Miocene, and that Cretaceous beds of salt are beneath the domes, and that they have risen due to differential block faulting and pressure. As the faulting is in the ancient mass of Llanoria, the fault lines are obscured by the overlying Cenozoic strata, and accordingly there is a lack among the salt domes of definite trend lines. In this connection, attention may be called to the very suggestive paper by Fohs and Robinson on "Structural and Stratigraphic Data of Northeast Texas Petroleum Area."[1]

Subsequent to writing the foregoing, I received a letter from G. D. Harris, calling my attention to his paper of 1909 in *Economic Geology*, and concluding with the following:

> Every bit of dome matter, so far as I know, is highly crystalline, whether lime, gypsum or sulphur. Who ever saw a piece of really *clastic rock* from a dome, much less a fossil? If these rocks are mere fragments of some very low-lying Permian or Triassic horizon, why are they not sometimes clastic? Again, it is rather strange that the salt is often 99 per cent plus pure NaCl. Queer deposit, is it not? that is, if formed as suggested above. Some keen physical chemist some day will find out the cause of "doming."

Even though I had read Harris's most excellent paper at the time of its appearance, I concluded to read it again. This I have now done. I am still of the conviction that the original salt is not older than Lower Cretaceous, and that it may actually be of late Eocene or early Oligocene time. In this connection, I want to bring to the fore what Harris says of epeirogenic movement taking place "at the close of the Vicksburg," and also to the presence of oölitic deposits and red marls that are gypsiferous, accompanying the Grand Gulf sandstones. Furthermore, to the fact that the Oligocene lies in troughs. Therefore I conclude once more that the origin of the salt domes appears to be connected with the inbreaking of the Gulf of Mexico, and that the Mississippi embayment, extending in early Eocene time into southern Illinois, was greatly restricted southward by elevation in the north, beginning markedly in Vicksburgian time. The bedded salt now risen into the domes may be connected with this crustal movement.

J. L. RICH: It would appear to be inevitable that, if salt ridges of anticlinal form such as those of the German area were produced by lateral compression

[1] *Econ. Geol.* (December, 1923), pp. 709–31.

at great depth, and the process of salt intrusion were continued until the salt rose through thick sediments to the surface, it would do so in the form of roughly circular plugs rather than as ridges, for some local point of weakness would develop and the salt would flow toward it from all sides. Therefore circular salt plugs rather than ridges should be expected where the source material lies at great depth.

M. G. CHENEY: As to the source of the large amounts of salt needed for the Gulf Coastal salt structures, there are certain considerations which indicate that the late Pennsylvanian and Permian are very possibly the time of these deposits. Llanoria must have been largely base leveled to furnish the Stanley shale, Jackfork sandstone, and early Strawn. Further, the strong overthrusting which produced the Ouachito Mountains and Choctou fault came during Pennsylvanian times and is quite positive evidence of the extensive subsidence of Llanoria to the southeast. Southern Oklahoma changed during the late Pennsylvanian from a generally synclinal to a general anticlinal structure, and the Permian marine waters migrated southward, westward, and northward. Isolation of parts of this southward migrating sea could have led to conditions favoring saline deposits.

G. H. CHADWICK: Drilling for natural gas in the southern peninsula of Ontario west of Niagara River has revealed an isolated lens of salt in the Salina formation which domes the overlying Onondaga limestone about 200 feet. This appears to be a true salt dome in youthful stage of growth.

SIDNEY POWERS: I can give additional information regarding this to anyone interested.

EDWARD BLOESCH: The geophysical methods may be helpful in locating and outlining salt domes in the Gulf Coastal region. Some of these, like the seismographic methods, seem to be still in the experimental stage. The gravity method has been used successfully in Europe. The method used in the oil field of Egbell in Czechoslovakia is an example published. Other information on these methods is more confidential and not generally available.

M. I. GOLDMAN: Determination of temperature gradient has been made by Van Orstrand, of the United States Geological Survey, at Damon Mound. I believe he obtained a gradient of something like 70 feet per degree of Fahrenheit. With a little encouragement from this Association and support from the companies here he could probably be readily induced to make more.

THE COTTON VALLEY, LOUISIANA, OIL FIELD

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ABSTRACT

The Cotton Valley, Louisiana, oil field has been an unusual field in the respect that the greater part of the structure produced large gas wells while at the outer extremity many gusher oil wells were brought in.

The first wells drilled were large, dry gas wells with a pressure of 1,200 pounds and 60,000,000 cubic feet of volume. Later, as the pressure decreased, these wells began to spray oil.

Many irregularities in production were encountered. Salt water occurred high on the structure and at shallower depths than found on the lower part of the structure.

These irregularities are explained as being due to the conditions under which the reservoir was deposited and irregular cementation of the sand grains.

The production is from the Blossom sand. Lower sands have not been thoroughly tested.

LOCATION

The Cotton Valley oil field is situated in the northern portion of Webster Parish, Louisiana, occupying the greater part of T. 21 N., R. 10 W., 1½ miles southeast of the town of Cotton Valley, 10 miles west of the Homer oil field, and 15 miles southwest of the Haynesville oil field.

The field extends over some 6,000 acres upon which, to date, 107 wells have been drilled, of which 66 are oil producers, 26 gas wells, and 8 salt-water wells and abandoned (Fig. 1).

HISTORY

The first well drilled leading to the discovery of the Cotton Valley field was the Webb-Merritt No. 1, located in Sec. 13, T. 21 N., R. 10 W., which came in August 25, 1922, as a 30,000,000-cubic foot gasser. Several other attempts were made in this area to obtain production without success. The Cotton Valley Syndicate obtained salt water in a 3,364-foot test in Sec. 16, T. 21 N., R. 10 W., in both the Blossom and Woodbine formations. The Palmer Corporation met with similar results in a test drilled below the Blossom sand in Section 29.

On November 10, 1923, the Oil Fields Gas Company brought in a 25,000,000-foot gasser in Section 14, making a slight spray of oil. This well was later taken over by the Louisiana Oil Refining Corporation, which retained the oil rights on this property. The light

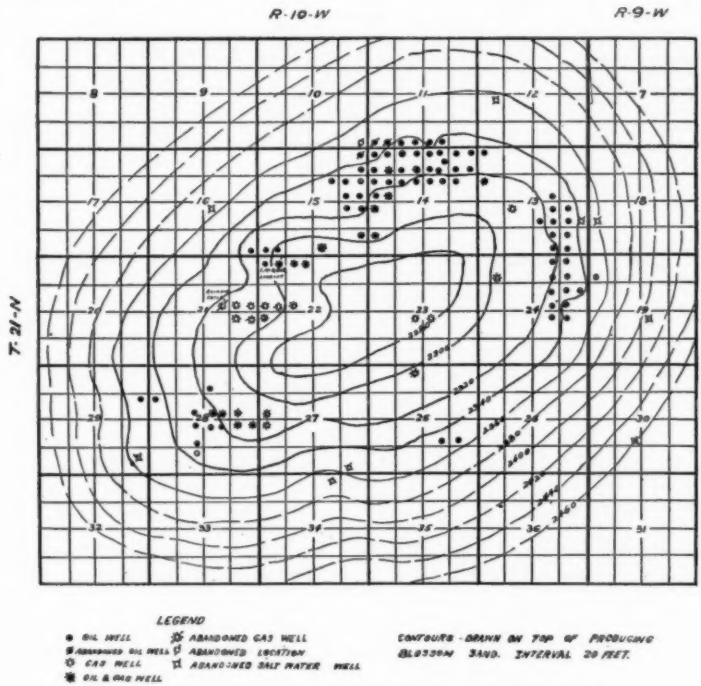

FIG. 1.—Sub-surface map of Cotton Valley Field, Webster Parish, La.

spray of oil increased, and this well proved to be the first commercial oil well in the field.

It was the opinion, generally, that Cotton Valley would be similar to the other North Louisiana gas fields producing large quantities of gas with showings of oil but not producing oil in commercial quantities. For this reason, many were slow to see its merits as an oil field. As a result, acreage was sold in large tracts and the greater portion of the best to the large oil companies. This has had a

significance in the development of the field as most of the companies have co-operated in the drilling program and eliminated unnecessary development.

TOPOGRAPHY AND DRAINAGE

The topography of the Cotton Valley field is marked by comparatively low-relief elevations ranging from 170 to 230 feet above sea-level. The lowest part of the field is the eastern extremity which borders on Davis slough of Dorcheat Bayou. There is nothing unusual about the topography of this field which might indicate that the beds beneath are folded.

STRATIGRAPHY

Surficial deposits of Quaternary age consisting of flood-plain deposits and terrace remnants cover the entire surface of the field, making it impossible to do reliable surface work to discern the subsurface structure.

The formations encountered by the drill in reaching the producing Blossom sand are the usual Eocene and Upper Cretaceous formations encountered elsewhere in North Louisiana down to the top of the Eagle Ford shales where the Blossom is entered.

One well in the field and several off structure have penetrated below these formations into the red shales above the Woodbine, but it is believed that none of these wells reached formations lower than Upper Cretaceous.

The correlation of well logs has been comparatively easy in the Cotton Valley field, due to the fact that a few companies own all the acreage and have been willing to co-operate with one another in trying to establish reliable markers by which accurate correlations could be made.

The base of the Annona chalk has been a reliable marker through northern Louisiana and can be used to advantage in the Cotton Valley field to determine the probable outcome of drilling wells. It necessitates close supervision during drilling in order to determine the base of the chalk, as usually there is a chalky shale just below the base of the hard chalk or lime formation which many of the field men mistake for a part of the chalk. The average interval between

the base of the Annona chalk and the top of the Blossom sand in Cotton Valley is 173 feet.

It was observed, however, that the first hard lime at the top of the Nacatoch formation ranging in depth between 1,600 and 1,700 feet below the surface, when logged accurately could be used to much greater advantage as information could thus be obtained before the well had reached a critical depth. Streaks of chalk or chalky shale occur 50–100 feet above this marker, but these formations are much softer and can be distinguished from the real lime formation below.

Other markers were used to some advantage although they appear to be less accurate than those just mentioned. They were the top of the Saratoga chalk and the top of the Annona chalk, ranging in depth from 1,950 to 2,050 feet and 2,175 to 2,250 feet, respectively, below the surface.

STRUCTURE

The Cotton Valley structure is one of a group of dome-shaped, anticlinal folds occupying a position on the western flank of the north Louisiana geosyncline. It is directly in line with the Bellevue and Haynesville structures and shows marked similarity to the Springhill-Shongaloo folds. However, it has been subject to more intense folding than the last-mentioned structures and shows more closure on the producing sand than Haynesville.

The subsurface structure of the field based on contours drawn on top of the producing sand shows a dome-shaped, anticlinal fold having a northeast-southwest major axis with steep, dipping flanks. Some minor irregularities are mapped, due, it is believed, more to depositional conditions than to structure. Closure of 170–80 feet is recorded, the higher part of the fold producing gas with a narrow band of oil around the entire perimeter of the fold. This band of oil produces commercial oil wells in a width not greater than three or four locations, being one of the outstanding features of the field and making new development hazardous.

DEVELOPMENTS

The first producing wells in the Cotton Valley field were subject to such large rock pressure that it was necessary to use flow boxes to separate the oil from the gas, and in most cases small chokes

($\frac{7}{8}$ to 2-inch diameter) were used in the flow lines. The initial rock pressure of the field when the first wells were brought in was 1,120 pounds, and wells had an open-flow capacity as high as 60,000,000 cubic feet.

It was required by the Conservation Commission that three strings of casing be set and cemented before drilling into the pay sand. The first string was set below 200 feet, the second string about 1,200 feet, and the third string between 2,450 and 2,500 feet, just above the producing sand. Later in the development of the field, after the rock pressure had decreased sufficiently, two strings only were required, providing the surface casing was set below 450 feet. This depth is below the fresh-water sands and anchors the casing in sufficiently hard formations to hold the remaining gas pressure. At the present time, the closed rock pressure of the field is less than 150 pounds.

The initial production of some of the largest wells of the field ranged from 1,000 to 10,000 barrels per day and were usually located on the outer edge of the field close to edge water. Most of these wells made clean oil only a few days, soon making as much as 40–50 per cent sediment and water. Some wells came in with enormous volumes of gas and spraying from 10 to 15 barrels of oil, showing very little increase over a period of months. Others, one location from wells producing large volumes of gas and oil, came in as pumpers scarcely having enough gas to clean the well. Some of these wells were deepened with the expectation of finding greater volumes of gas, but they remained pumpers even after being drilled to a lower subsea depth than wells having plenty of gas and apparently holding the same position on the structure. Usually these smaller wells pumped cleaner oil with less salt water and sediment and gave less sand trouble than the larger producers. In the gusher-type wells, much trouble was experienced in the bridging over of the sand, and it was necessary to clean the wells out every few days in order to keep them flowing.

As the gas pressure was released and the wells stopped flowing, whenever the fluid stood at a sufficient height, air-compressor plants were installed, and large volumes of fluid were produced, a large percentage of it being sediment and water.

Early in the development of the field, it became evident that wells drilled below a subsea depth of 2,340–45 feet would produce water. This was especially true near the edge of the field, and in some few instances water was produced in large quantities high on the fold. Most of the gushers were located on the edge of the field and were drilled below a 2,340-foot subsea depth. Some wells drilled high on the structure produced oil several months without any water, although they were drilled below the supposed water-level.

The Humble Oil and Refining Company's Babb No. 2, in Sec. 14, R. 21 N., R. 10 W., was an example of this type of well. It was drilled to a depth of 2,350 feet, subsea, and produced several months, making under 5 per cent sediment and water.

Some wells in the field, located high structurally, produced large volumes of gas and appreciable amounts of salt water with only a showing of oil. The Raymond-Coyle well in Sec. 21, T. 21 N., R. 10 W., was an example of this type. This well was drilled to a subsea depth of 2,335 feet and made 20,000,000 cubic feet of gas and a large quantity of salt water.

Another unusual well was the Louisiana Oil Refining Corporation's Lindsay No. 1, located in Sec. 22, T. 21 N., R. 10 W. The top of the sand in this well was logged higher than an offset well producing dry gas. It came in spraying from 75 to 100 barrels of oil and 35,000,000 cubic feet of gas. In a few days its flow increased and it started producing 1,500 barrels of fluid with, at first, only a small percentage of sediment and water. The Hude and Aarnes' Cox No. 1, an offset dry gasser, was deepened to within a few feet of the depth of this well and showed only a small amount of oil, which increased very slightly when allowed to blow for several weeks.

The Louisiana Oil Refining Corporation's Lindsay well was drilled to a subsea depth of 2,346 feet and has been one of the best wells in the field, flowing 91,000 barrels of pipe-line oil before being put on the pump.

PRODUCING SAND

The producing horizon of this field is in the upper part of the Eagle Ford shales and is known as the Blossom sand. This sand is from 40 to 50 feet in thickness and is made up of irregular quartz

grains with a small percentage of glauconite. It is light gray to greenish yellow in color and contains a varying amount of calcareous cementing material.

At the top of the sand, and at varying depths within, the sand grains are closely cemented, forming hard caps. The cap at the top of the sand is usually from 2 to 4 feet thick and is unmistakable. At some points in the field no cap is to be found, the sand is soft, and the top is easily passed up. In some parts of the field, 8–10 feet of sandy shale occur above the producing sand. In other parts, a hard shale or gumbo varying in thickness is found.

It is apparent, upon examination of a number of cores taken in the field, that the producing sand was laid down in comparatively shallow water with changing shore lines. These cores show streaks of shale interbedded in the sand, and in some instances the shale predominates.

Several wells in the field have logged distinct shale and gumbo breaks in the sand from 2 to 12 feet thick. These breaks do not come at regular intervals in the sand. It has been suggested that possibly a break occurs between the gas and oil sand and that it is necessary to penetrate this break in order to produce oil. Shale and gumbo streaks have occurred only at irregular intervals through the field, and most of the wells do not encounter any such distinct breaks.

An attempt has also been made to correlate the hard caps in the sand but without success. These numerous caps within the sand are probably hard shale or indurated sand, the latter being formed by waters carrying calcareous cementing material, percolating through the sand and depositing the lime between the grains in an irregular manner.

It is apparent that a reservoir of the type here described cannot be expected to produce in an ideal manner, and these depositional irregularities are undoubtedly the cause of many of the phenomenal conditions experienced in the production of the Cotton Valley field. The irregular occurrence of salt water in the sand has been explained by some as the result of coning of bottom water caused by the enormous suction of the gas in larger wells. This explanation does not seem to explain fully many of the conditions of the field, such as the production of salt water high on the structure in wells drilled to a

shallow depth; also, bottom water does not seem to occur in appreciable amounts high on the anticline.

It is believed that the conditions under which the reservoir sand was deposited and the irregular cementation of the sand grains have had more to do with these unusual conditions than any other. A large amount of silt and mud was deposited between the sand grains, and this with subsequent percolating calcareous waters caused a wide variation in the size of the pore spaces between the sand grains. Some of these spaces being more susceptible to the retention of water than to oil or gas, the water was retained in the pores and was not affected by the laws of gravitational separation. There may even be depositional conditions existing within the sand which would make lenses of the reservoir impervious to migration of oil, gas, or water. This variation in the porosity of the sand might also explain why some wells offsetting small oil wells or dry gas wells came in large producers.

As previously noted, the oil occupies a narrow band around the entire perimeter of the structure, only a small showing of oil having been found on the higher part. From all appearances, the Louisiana Oil Refining Corporation's Lindsay well is an exception to this statement as the top of the sand was logged higher than some dry gassers. This can be explained by an apparent thickening of the sand in this part of the field. The interval between the base of the Annona chalk and the top of the sand in this well is less than the average interval for the field.

There has been considerable discussion as to the probability of the oil migrating from the outer extremities to the top of the fold after the gas pressure has been depleted sufficiently and those wells now making dry gas eventually becoming oil producers. This is problematical, and it does not seem probable that such will occur. With so large a part of the higher portion of the structure apparently barren of oil and with the comparatively small amount of oil on the outer rim drained by so many wells, it is perceived that most of the oil will be taken from the ground before much migration can take place into the higher parts of the structure; also, most of the oil which is allowed to migrate will be utilized in saturating the sand higher on the structure. This saturation will probably not reach a point sufficient to produce wells larger than a few barrels.

Several wells drilled on the edge of the gas area which came in making large volumes of gas and a few barrels of oil have increased their flow, now that the rock pressure is low, to from 50 to 75 barrels of oil per day, but they do not have the appearance of ever making large wells.

PRODUCTION

Up to and including December 31, 1924, 1,479,162 barrels of pipe-line oil were run from the Cotton Valley field. At this time there were 110,980 barrels of pipe-line oil in storage, making a grand total of 1,590,142 barrels of pipe-line oil produced in the field in 1924.

The peak of production was apparently reached in the month of November, 1924. The pipe-line runs show at that time a total of

TABLE I

ANALYSIS OF COTTON VALLEY CRUDE OIL

(Gravity, 29.8° Bé.)

Gasoline	None
Heavy naphtha	2.5
Kerosene	7.5
Gas oil	30.0
Fuel oil	60.0
Total	100.0

270,529 barrels with an estimated 135,234 barrels of pipe-line oil in storage in the field.

It is impossible to obtain an accurate estimate of the barrels per acre yield or the ultimate production of the field, due to the large gas-producing area and the irregular production of the field.

The Woodley Petroleum Company has, beyond a doubt, one of the best 20-acre leases in the field. Three wells, up to December 31, 1924, produced 260,780 barrels of pipe-line oil. This gives the remarkable figure of 13,036 barrels per acre, which is probably many thousand barrels more than the average barrel per acre yield of the entire field.

The Ohio Oil Company's Bodcau No. 2, in Sec. 15, T. 21, N. R. 10 W., produced 101,000 barrels during 1924. Other large wells producing over 60,000 barrels of oil were the Louisiana Oil Refining Corporation's Lindsay well in Section 22, Alabama Petroleum Com-

pany–Pardee B-2, Section 24, and the Gulf Refining Company–Hodge No. 1, in Section 11.

Tests made on the gasoline content of Cotton Valley oil show very little gasoline, and the cracking process must be resorted to in order to obtain gasoline from this oil.

The following analysis by the Louisiana Oil Refining Corporation shows the contents of oil:

DEEP SANDS

The Woodbine formation of the Cotton Valley field has shown several sands which may prove productive when thoroughly tested.

The Cotton Valley Syndicate–Sidney No. 1, in Sec. 16, T. 21 N., R. 10 W., encountered 40 feet of porous sand, 730 feet below the top of the present producing sand, at 3,315–55 feet, which tested salt water.

The Palmer Corporation–Miller No. 1, in Sec. 29, T. 21. N, R. 10 W., found 10 feet of broken sand and shale at 3,342 feet. This well was deepened to 3,471 feet and encountered 18 feet of coarse, green sand at 3,453 feet. Six-inch casing was set, and the sand tested salt water with a trace of oil.

The United Central Oil Corporation–Gleason No. 1, Sec. 31, T. 22 N., R. 9 W., logged 13 feet of broken sand and lime at 3,336–49 feet and also 30 feet of sand at 3,422–52 feet. These sands are found interbedded with the red shales, and in most cases salt water was contained in them.

All of these wells were drilled off structure and for this reason cannot be considered as condemning the Woodbine.

The Raymond *et al.*–Coyle No. 1, in Sec. 21, T. 21 N., R. 10 W., obtained a gas and salt-water flow with a small amount of oil in the Blossom sand and was deepened to 3,374 feet. It encountered a streak of sand at 3,287–91 feet, which was not cored or tested, but from all appearances of the cuttings, it did not contain any oil. This well was near the crest of the structure as drawn on the Blossom sand.

The sands of the Woodbine, as found in other fields of north Louisiana, appear to be lenticular. This is probably the case in Cotton Valley and explains the fact that the Raymond-Coyle well

did not encounter the thickness of sand logged by the Cotton Valley Syndicate–Sidney well in Section 16, at 3,315 feet. This sand had evidently pinched out in the Palmer Corporation–Miller well in Section 29, as only a 10-foot thickness of broken sand and shale was found here.

Therefore it follows that better sand conditions may be found at other points on the structure and that the Raymond–Coyle well does not condemn this sand. Also, it was not carried deep enough to test the lower sand found in the Palmer–Miller well and cannot be considered a thorough test.

A STUDY OF SOME UPPER CRETACEOUS SEDIMENTATION AND DIASTROPHISM IN MONTANA

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ABSTRACT

The presence of a considerable variation in the thickness of the interval from the base of the Eagle sandstone of Montana time to the top of the Kootenai or Cloverly of Lower Cretaceous age has long been recognized over east-central Montana. As far as is known, however, no systematic study has been published showing the regional variation in thickness or the possible causes of such a phenomenon. This article is therefore an attempt to show by discussion and graphical representation the regional variation of the interval previously described, an interval formerly supposed to include only the Colorado formation of Upper Cretaceous age, but now known to embrace, over the southern part of the state at least, sediments of Montana time. There is also shown overloading of sediments over certain parts of the area and the resultant effects on diastrophism and sedimentation, from which additional light is shed on the problem of correlation of the sediments grading from Colorado to Montana time. In order to show some effects of the difference in sedimentation, it has been thought advisable to outline roughly the probable conditions immediately prior to Dakota time, as well as the continued deposition into Montana time, as criteria upon which to draw generalized conclusions. It is suggested that more detailed study of isopach lines may throw more light on proper subsurface mapping, especially of relatively large areas, as well as being an aid in the study of the deposition of sediments.

INTRODUCTION

The presence of a considerable variation in the interval from the base of the Eagle sandstone of Montana time to the top of the Kootenai of Lower Cretaceous age has been recognized for some time over eastern Montana. As far as known, however, no systematic attempt has been made to interpret this condition. After a considerable study of the geology of eastern Montana, it appeared that the condition indicated by this phenomenon offered a basis for one of the most interesting geological problems of the region.

A preliminary interpretation of the variation of the thickness of the Colorado shales was begun by the senior author over two years ago. At that time insufficient data had been collected to permit even an approximation of the conditions that exist. Since that time sufficient data have been obtained to make a fair regional delinea-

tion of conditions, and this paper is submitted as such, with realization that it may be subjected to changes as other data are obtained.

DESCRIPTION OF WORKING DATA

The data, on which the variation in the interval between the Eagle sandstone and the base of the Dakota horizon is based, were obtained from measured stratigraphic sections at points of outcrop and logs of numerous wells. The base of the Eagle sandstone is taken as the top of the Colorado shales over the greater part of the area, except in that part lying along the southern boundary of Montana and extending southward into Wyoming. Here it has been found that the Eagle sandstone lies on beds that appear to be a transition stage from Colorado to Montana time, designated by W. T. Thom, Jr., as the Telegraph Creek formation.[1] The fauna of this formation has been studied by J. B. Reeside, Jr.,[2] who has shown that it contains fossils common to both Colorado and Montana time.

The base of the Dakota horizon is here considered as the first distinct change in the lithology from sandstone to white or pink shales, or where the sandstone is absent, from the dark shales or sandy shales to white or pink shale. This line of demarcation is quite distinct throughout the entire district considered. What may be the hypothetical base of the Dakota group elsewhere to the south and east does not seem applicable to Montana. There seems no justification here for placing any of the sandstones lying below the white or pink shales at the top of the Kootenai in the Dakota group.

Because of the necessity of an arbitrary use of certain data, it is advisable to explain somewhat in detail the basis for the interpretation. Where the data are well substantiated and of a definite character, reference will be made to the sources of information only as a matter of record.

The indicated conditions in the vicinity of the Cedar Creek anticline in eastern Montana are somewhat hypothetical as they are based on one measured section on the northwestern side of the Black Hills and two well logs on the Cedar Creek anticline, both of which started a short distance below the Fox Hills sandstone and penetrated the Fuson shale.

[1] W. T. Thom, Jr., *U. S. Geol. Surv. Bull. 726-B.*

[2] J. B. Reeside, *U. S. Geol. Surv. Prof. Paper 132.*

The better one of these two logs is that of the well drilled by the Absaroka Oil Development Company in Sec. 24, T. 4 N., R. 61 E. (locality 29),[1] which gives fairly accurate data as to the thickness from the base of the Pierre shale to the top of the Fuson shale. The formations in this well were accurately sampled, and careful tests and study lead the authors to believe that the top of the Niobrara was encountered at a depth of about 1,420 feet, just below a sandy shale horizon carrying considerable gas, which is believed to be equivalent to the Eagle sandstone horizon. The Dakota sandstone was encountered at 3,913 feet and the top of the Fuson shale at 3,926 feet. This shows the interval under consideration to be 2,506 feet.

The well of the Montana Yellowstone Oil Company near Glendive, in Sec. 4, T. 14, N., R. 55 E. (locality 28), was drilled with a rotary machine so that only small dependence can be placed in the log. After careful comparison with the well just discussed, however, we have arrived at the conclusion that the interval is approximately 2,653 feet.

On the Porcupine dome (locality 19) in central Montana the thickness assigned to the Colorado group is estimated at 2,050 feet. This estimate is thought to be reasonably accurate. It is based on well logs supplemented by measured sections down to the horizon at which the various wells start. Here the Eagle sandstone is absent, and the base of the Montana group is thought to occur at a conglomerate, 1–2 feet in thickness, composed of well-rounded pebbles in a sandy matrix similar in texture and character to those associated with the Eagle sandstone elsewhere in Montana. There is also a distinct change in the lithologic character of sediments immediately above and below the conglomerate. Those above are yellow to brown sandy shales and some calcareous beds, and those below are characteristic shales of the Upper Colorado, interstratified with brown and red concretionary zones. A search for fossils above the conglomerate has given little aid, although one well-preserved specimen has been found which appears to be *Cardium speciosum*, a form occurring elsewhere in the Claggett and Eagle. Whether or

[1] In all cases "locality numbers" refer to locations designated on the isopach map (Plate II) and to the list of data on p. 891.

not the occurrence of this conglomerate indicates an unconformity is open to argument. It is certain, however, that there must have been a distinct change in water currents and deposition to have produced a conglomerate in what was otherwise apparently a deep-sea area far removed from any known shore. The pebbles are composed largely of well-rounded cherts and allied calcareous and siliceous materials, with an entire absence of any igneous material.

The interval indicated a short distance northeast of Hardin (locality 14) as 3,056 feet is based on a composite section and well log. The well was drilled by the Superior Oil and Coal Company. It reached the top of the Kootenai at a depth of 2,450 feet. Late in the year 1924 a section of the sediments was measured from the base of the Judith River sandstone to the top of the well. At this point the Eagle sandstone as a recognizable unit is absent. However, we have taken a thin sandstone 552 feet below the base of the Judith River formation as the approximate equivalent of the Eagle horizon. As this interval is somewhat greater than measured sections farther west where the Claggett is known to be 468 feet[1] thick, and as it is greater than the estimate of 400 feet made by Rogers and Lee,[2] it seems reasonable to believe that the interval of 3,056 feet as representative of the strata between the Eagle horizon and base of the Dakota cannot be far wrong. Additional evidence that the thin sandstone represents the Eagle horizon is found in the difference in the lithologic character of sediments above and below. Above, the shales are characteristic of the Claggett, containing abundant yellow concretionary zones; and below, the sandy shales and thin calcareous beds are characteristic of the Telegraph Creek formation at the type locality.

The interval representing the Colorado shales (locality 20) on the Alice dome is based on the study of a log prepared after a careful examination of the drill cuttings from a well drilled in Sec. 10, T. 13 N., R. 34 E. The evidence furnished by this log leaves little doubt as to the accuracy of the interval given as 2,077 feet.

The interval taken for the Ingomar anticline (locality 18) is based on a careful study of samples from which the log of the well

[1] Sections measured by A. M. Lloyd near Toluca.

[2] Estimated by G. S. Rogers and Wallace Lee, *U. S. Geol. Surv. Bull. 749*, p. 13.

drilled by the Absaroka Oil Development Company was compiled. The change in the character of the sediments above and below a sandstone found at 560–70 feet in this log strongly indicates that it occurs at the horizon of the Eagle sandstone. If this interpretation is correct, then the interval from the Eagle to the base of the Dakota is 2,330 feet.

At all other localities the data used are of such character that there is little chance for any important error. Since this is true, it is neither advisable nor necessary to enter into a detailed discussion of the data used at each locality. However, in order that the sources of information may be available to the reader, a tabulation is given on page 891.

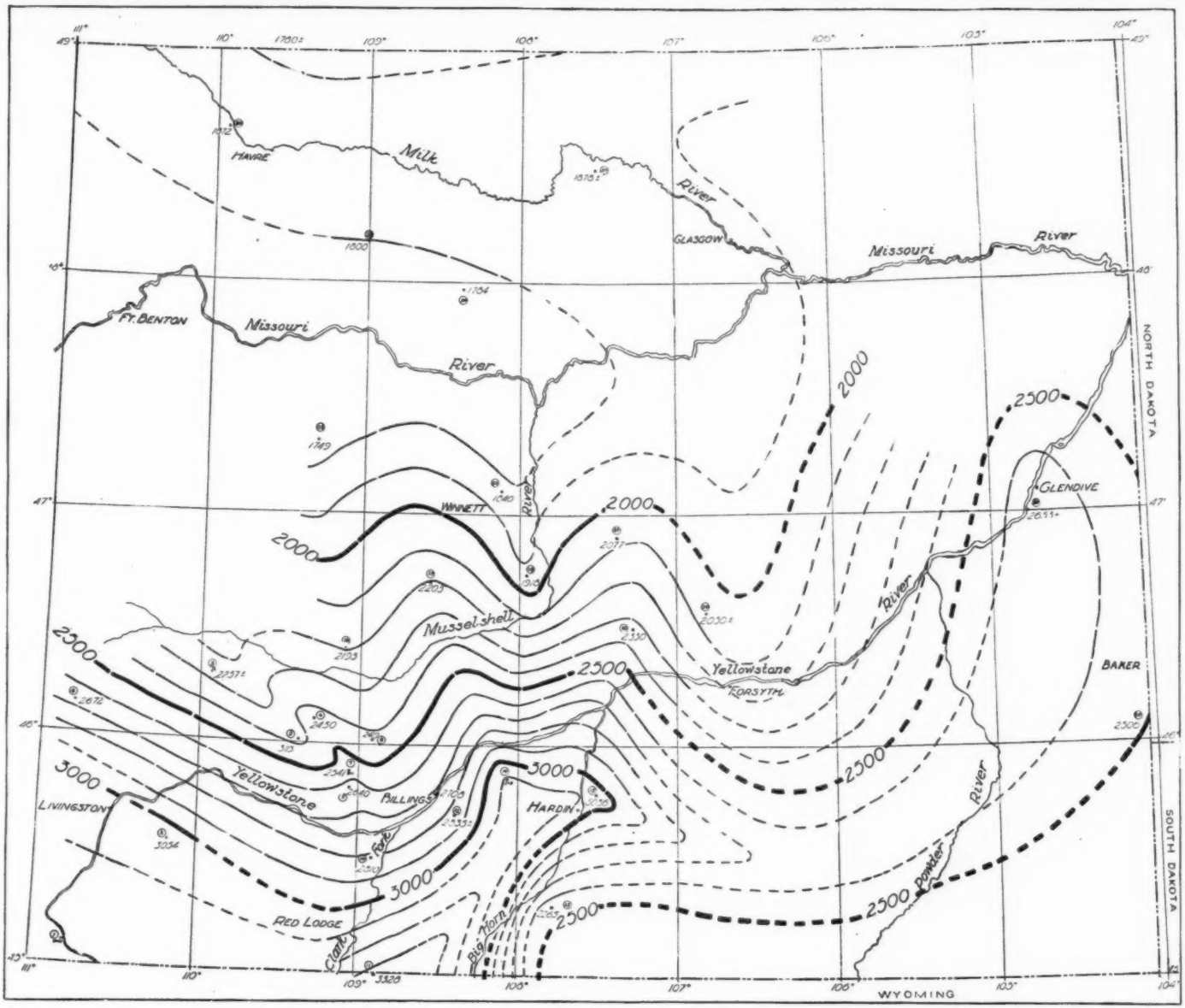
INTERPRETATION BY ISOPACHS

The term "isopach" is used to designate lines through points of equal thickness. By reference to Plate 11, it will be seen that the interval is the least over a broad area extending over north-central Montana and northward into Canada. The area included within the 1,800-foot isopach may include a somewhat restricted area of less thickness in the region around Great Falls and immediately east and northeast. The data obtainable at present for that area are more or less questionable and have not been used for that reason.

To the east and southeast of the area embraced by the 1,800-foot interval there is a gradual thickening. The isopachs swing from a general east-and-west direction to the north, indicating a broad, arching effect which extends roughly through the area occupied by the Porcupine dome. The increase in thickness continues eastward to a point near the north end of the Cedar Creek anticline, where the greatest-known interval in that area is reached, amounting to over 2,600 feet.

It is noticeable that there is a tendency for a southward swing in the isopachs producing an effect of arches plunging to the south. This condition is especially noticeable in the areas centering around the Porcupine dome, in the region of the Cat Creek oil field, and in the district extending southward from the Big Snowy Mountains to the district between the towns of Columbus and Billings.

In the vicinity of the Cat Creek oil field there is a rather marked



Eastern Montana–Isopach Map, showing variation between base of Eagle and base of Dakota

TABLE I

RECORDS OF THE INTERVAL FROM THE BASE OF THE EAGLE TO THE BASE OF THE DAKOTA IN MONTANA

Locality No.	Location	Interval from Base of Eagle Sand to Base of Dakota, in Feet	Source of Information
1.....	Sec. 36, T. 8 S., R. 7 E.	3,142	W. R. Calvert, "Electric Coal Field," *U.S. Geol. Surv. Bull. 471*
2.....	Boulder River	3,054	Roy Lebkicker, and in part by R. E. Shutt
3.....	T. 6 N., R. 14 E.	2,257	C. F. Bowen, *U. S. Geol. Surv. Bull. 691*
4.....	Sec. 35, T. 5 N., R. 7 E.	2,672	A. M. Lloyd, junior author, *Section and Well Log—Mid-Northern Oil Co.*
5.....	Sec. 17, T. 3 N., R. 19 E.	2,381	*Log—Mid West Refining Co.*
6.....	Sec. 13, T. 4 N., R. 19 E.	2,430	*Log—Mid-Northern Oil Co.* and measured section
7.....	Sec. 35, T. 2 N., R. 21 E.	2,541	*Log—Barnsdall-Foster Oil Co.*
8.....	Sec. 13, T. 3 N., R. 22 E.	2,419	*Log—Securities Producing Co.*
9.....	Sec. 26, T. 1 N., R. 21 E.	2,640	*Log—Mid West Refining Co.*
10.....	Sec. 8, T. 4 S., R. 23 E.	2,810	*Log—Hoosier Oil & Gas Co.* and section by A. M. Lloyd
11.....	Elk Basin, Wyo.	3,328	E. L. Estabrook, *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 7, No. 2, pp. 96 and 97
12.....	Sec. 4, T. 2 S., R. 27 E.	2,835	*Log—Mid-Northern Oil Co.* and section by A. M. Lloyd
13.....	Soap Creek	2,565	W. T. Thom, Jr., *U. S. Geol. Surv. Bull. 751-C*, pp. 90 and 91
14.....	Sec. 11, T. 1 N., R. 29 E.	3,115	*Log—Absaroka Oil Development Co.*
15.....	Sec. 33, T. 1 N., R. 34 E.	3,056	*Log—Superior Oil & Coal Co.* and section by A. M. Lloyd
16.....	Secs. 29 and 32, T. 8 N., R. 21 E.	2,195	*Log—Tri-City Oil Co.* and partial section by A. M. Lloyd
17.....	T. 11 N., R. 25 E.	2,203	*Log—Devil's Dome Well* and section by A. M. Lloyd
18.....	Sec. 5, T. 11 N., R. 30 E.	1,918	*Log—Ohio Oil Co.* and section by V. A. Gilles
19.....	Sec. 26, T. 9 N., R. 35 E.	2,330	*Log—Absaroka Oil Development Co.*
20.....	Ts. 9 and 10 N., R. 39 E.	2,050	*Log—Steller Oil & Gas Co.* and section by A. M. Lloyd
21.....	Sec. 10, T. 13 N., R. 34 E.	2,077	*Log—Absaroka Oil Development Co.*
22.....	T. 16 N., R. 28 E.	1,840	Section by Reeves, *U. S. Geol. Surv. Bull. 751-C*, pp. 90–91
23.....	Sec. 16, T. 18 N., R. 19 E.	1,749	*Log—California Co.*
24.....	T. 26 N., R. 26 E.	1,784	Section by A. A. Hammer and A. M. Lloyd
25.....	T. 28 N., R. 21 E.	1,800	Section by Reeves, *U. S. Geol. Surv. Bull. 751-C*, pp. 90–91
26.....	Sec. 31, T. 34 N., R. 14 E.	1,872	*Log—Frantz Corp.*
27.....	Sec. 35, T. 32 N., R. 32 E.	1,878	*Log—Bowdoin Oil & Gas Co.* No. 2
28.....	Sec. 4, T. 14 N., R. 55 E.	2,653	*Log—Montana-Yellowstone Oil Co.*
29.....	Sec. 24, T. 4 N., R. 61 E.	2,506	*Log—Absaroka Oil Development Co.*

"nose" produced by the abrupt change in the direction of the isopachs, indicating an arching of strata during Colorado time. The axis of the early arch runs in approximately a north-and-south direction. The axis of the Cat Creek anticline crosses the older axis at an angle somewhat less than 90° in a direction slightly north of west. It is possible that the crossing of these axes has produced a subsurface doming that may have some bearing on the occurrence of oil in that anticline.

Southward from the 1,800-foot isopach the interval between the base of the Eagle sandstone and the base of the Dakota gradually increases until at the boundary line between Montana and Wyoming it has reached a thickness of over 3,300 feet. Along the north boundary of the Yellowstone National Park it is over 3,100 feet.

Whether the diastrophism occurring during Colorado time caused a rising of the sea bottom in northern Montana or a subsidence over southern Montana and the Big Horn Basin of Wyoming is of small moment, since either would have produced approximately the same conditions as to the deposition of sediments, so long as the sea bed was submerged throughout the entire area. However, the movement is considered here as a subsidence over the southern part of the area rather than an "upwarping" over the northern part. This conclusion seems warranted since the interval under discussion remains almost a constant from the 1,800-foot isopach north into Canada, without any evidence to indicate other than a continuous continental bench upon which the Colorado sediments were deposited.

The southern boundaries of this basin have not been studied, but it is probable that as far as true Colorado time is concerned the deeper part did not extend a great distance to the south, since beds assigned to that horizon are only 2,389 feet thick at Salt Creek,[1] and 2,482 feet in the Lost Soldier field,[2] as compared to about 3,574 feet in the center of the Big Horn Basin.[3] The western limit of the basin is not known, but it is thought likely that it extended far enough west, at least, to include the area now occupied by the Yellowstone

[1] C. H. Wegeman, *U. S. Geol. Surv. Bull. 691*, p. 13.

[2] A. E. Fath and G. F. Moulton, *U. S. Geol. Surv. Bull. 756*, pp. 17–24.

[3] C. T. Lupton, *U. S. Geol. Surv. Bull. 621*, pp. 167–72.

National Park. This condition is indicated by stratigraphic sections measured at Electric, Montana[1] (locality 1), and along the Boulder River[2] (locality 2). At these points the sediments assignable to the Colorado average about 2,800 feet in thickness. If to this be added a series of strata believed to be equivalent to the Telegraph Creek formation, having an average thickness of about 300 feet, the interval from the base of the Eagle to the base of the Dakota horizon is approximately 3,100 feet.

To the north and east an arm of the sea or estuary seems to have extended as far as the northern end of the Cedar Creek anticline, near the town of Glendive, Montana. From the deepest part of this area the interval decreases rapidly toward the Black Hills and eastward into North Dakota and South Dakota, where a minimum thickness of less than 1,000 feet is found in the eastern part of these states.

GEOLOGICAL HISTORY

Following this outline of the existing conditions relative to the interval from the base of the Eagle sandstone to the base of the Dakota horizon, the question naturally arises as to the probable causes that produced the variation in thickness.

In order to form a clear conception of occurrences during early Upper Cretaceous time, it is advisable to know something of the conditions at the close of the Lower Cretaceous. Between Triassic time, as represented by the Chugwater in Montana and the deposition of the Ellis or Sundance of late Jurassic age, there is a hiatus represented by early Jurassic time, during which a great period of base-leveling occurred.[3] When the late Jurassic seas encroached over the area, deposition took place over the more or less eroded surfaces of strata represented by parts, at least, of all formations present in east-central Montana and northwestern Wyoming from Madison to Chugwater time (see Fig. 1).

Deposition appears to have been continuous from the time of the encroachment of the late Jurassic sea throughout Ellis, Morrison,

[1] W. R. Calvert, *U. S. Geol. Surv. Bull. 471*, p. 413.

[2] Taken from a measured section by Roy Lebkicker, California Co., and an estimated section by R. E. Shutt on a reconnaissance in southern Montana.

[3] D. D. Condit, *U. S. Geol. Surv. Prof. Paper 120*, pp. 113–14.

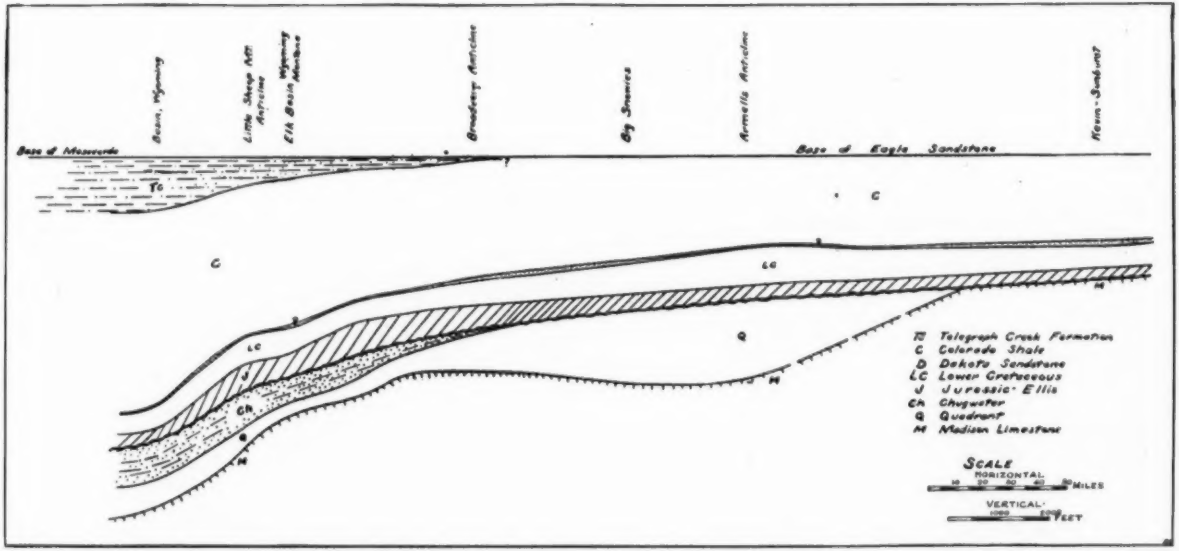


FIG. 1—Cross-section from Big Horn Basin, Wyoming, to Sweetgrass Arch, Montana, illustrating the variation in thickness of sediments from Madison to Eagle time, and the unconformity between Upper Jurrassic and older beds.

and Kootenai time or up to the close of the Lower Cretaceous. The deposition of these sediments had therefore "ironed out," as it were, the irregular surface that existed at the beginning of late Jurassic time, so that at the close of Kootenai time the surface was a broad, monotonous plain,[1] almost if not entirely covered with shallow, brackish and fresh waters. The plain was widespread, extending far beyond the limits of the area covered by this article.

Briefly, this was the condition at the time of the great subsidence that occurred with the encroachment of the Upper Cretaceous sea. It was upon this plain and in the changing water currents of the encroaching Colorado sea that the Dakota sediments were deposited, partly perhaps in fresh and brackish waters, and partly in marine waters. As subsidence continued and the Colorado sea became deeper, the change resulted in the constant and uniform deposition of the Thermopolis shales, without any apparent unconformity.[2]

If the area in south-central Montana and northwestern Wyoming had been a basin of greater subsidence than other parts of the sea at the beginning of Upper Cretaceous time, it is evident that a regional angular unconformity would have occurred between the Kootenai and the Thermopolis shales. A study by the writers of the points of outcrop of the transition of Kootenai to Colorado from the Big Horn Basin to northern Montana has failed to indicate any unconformable relation between the two, and the similarity shown by the study of many well-logs to the measured sections leaves no room to assume any other than continuous deposition.

That subsidence began just at or near the beginning of Upper Cretaceous time and was continuous throughout Colorado time and later is shown by the similarity in the changes in thickness of the various subdivisions of the Colorado group over the entire area. Sufficient data have not been secured to differentiate the various subdivisions, one from the other, over large areas. For the purposes here needed the Colorado has been divided on general lines as follows: (1) a lower part from the base of the Dakota horizon to the top of the Frontier formation; (2) a middle part from the top of the Frontier formation to the base of the Telegraph Creek beds;

[1] Ernest G. Robinson, *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 8, No. 5, pp. 555–57.

[2] Ernest G. Robinson, *op. cit.*, p. 555.

(3) an upper part consisting of the Telegraph Creek beds and contemporaneous sediments.

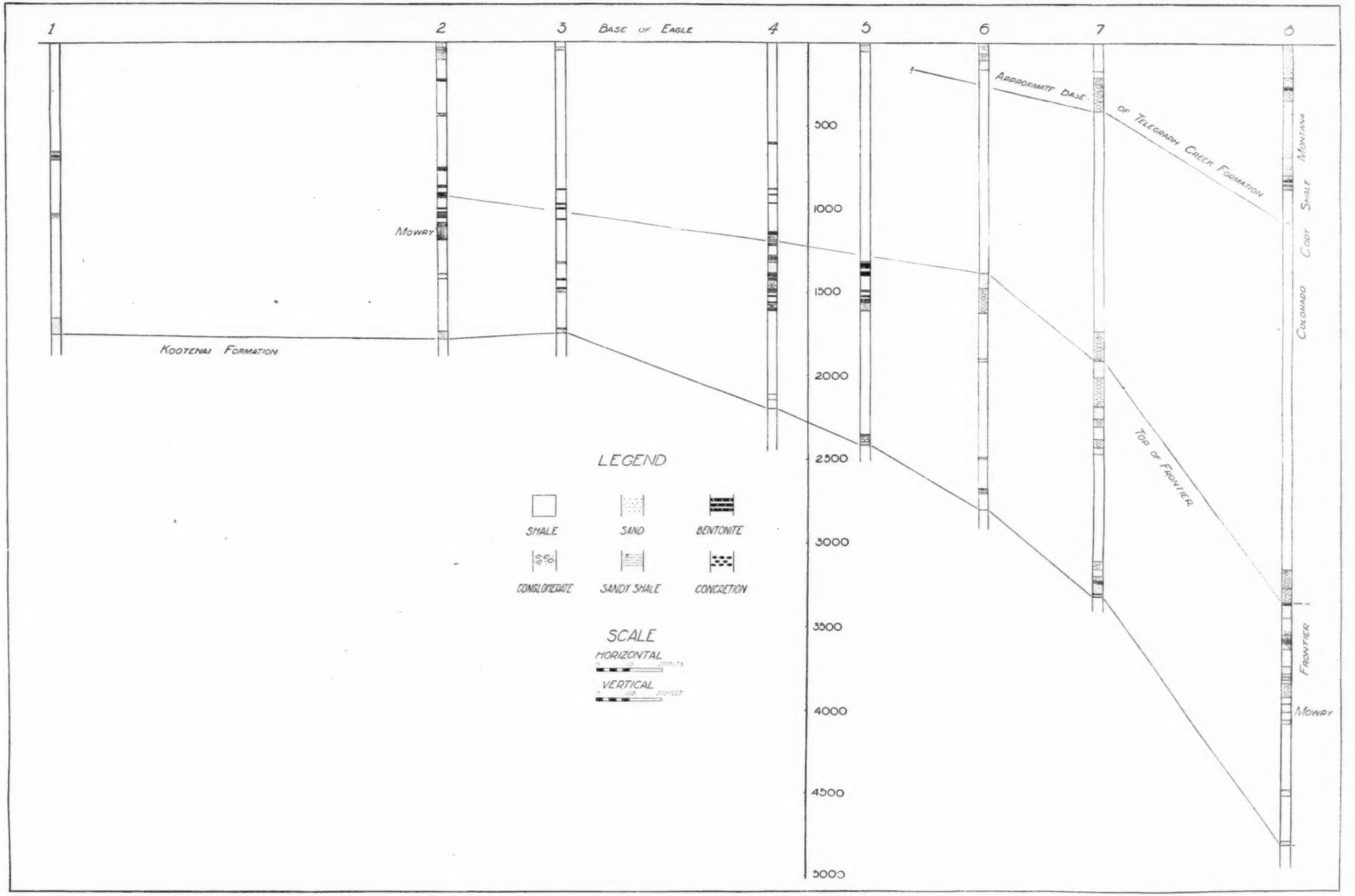
By reference to Plate 12, it will be seen that in the case of all three groups there is a thickening from north to south. Between the close of Kootenai time and the close of Frontier time a subsidence is indicated by the variation in the thickness of sediments occupying that interval. In the vicinity of Elk Basin, Wyoming, the interval is 1,420 feet. From that point there is a gradual thinning northward until the Bearpaw and Little Rocky Mountains are reached, where the interval is 850 feet.

In the case of the "Middle Part," the interval at Elk Basin, Wyoming, is 1,500 feet. This series of beds thins rapidly to the north, until in the Bearpaw Mountains the interval is around 800–900 feet. Reeves[1] has indicated that the Mosby sandstone may be equivalent to the Greenhorn limestone of the Black Hills section, but for the purpose of this paper it has been taken as the approximate equivalent of the upper limit of the Frontier.

In the case of the "Upper Part," there are so few data based on paleontological evidence that for the purpose here needed the zone of sandy shale and thin limestone occurring just below the basal member of the Eagle sandstone is placed as the equivalent of the Telegraph Creek beds. The northern and eastern limits of this series of beds are not known. It is likely that they thin rapidly to the north. At Elk Basin, Wyoming, the base of the Telegraph Creek formation is thought to be at the bottom of a series of light-colored sandy shales and streaks of calcareous concretions about 200 feet thick, occurring just below the Elk Basin sandstone. If to this is added the interval of about 200 feet from the base of the Elk Basin sandstone to the base of the Eagle, the thickness assignable to the Telegraph Creek formation at Elk Basin is 400 feet. C. J. Hares[2] has called attention to the series of beds below the Elk Basin sandstone which he assigns to the Montana division. The authors believe that the Elk Basin sandstone and shales above, up to the base of the lower member of the Eagle sandstone, are assignable to the Tele-

[1] Frank Reeves, *U. S. Geol. Surv. Bull. 751-C*, p. 88.

[2] Unpublished stratigraphic section near Elk Basin.



Explanation: (1) Kevin-Sunburst Field; (2) Bearpaw Mountain; (3) Moulton Dome; (4) Women's Pocket Anticline; (5) Broadview Anticline; (6) Joliet Well Log and Section; (7) Elk Basin Anticline; (8) Basin Wyoming

graph Creek formation because of the similarity of the basal sandstones and coal beds to the section farther north in Montana.

On the Crow Indian Reservation at the type locality, the Telegraph Creek beds have a maximum thickness of about 320 feet; on Boulder River they are about 260 feet; and near Electric, Montana, beds which appear to be equivalent to the Telegraph Creek beds are 259 feet thick. The interpretation on both Boulder River and at Electric is based on the stratigraphic position below the Eagle sandstone and above beds in which typical Colorado fossils have been found. Almost everywhere throughout south-central Montana the basal part of the Eagle consists of two massive sandstones, between which occurs a bed of coal, at some places workable, and at others a low-grade product or a zone of carbonaceous shale. Since this series can be traced with only a few breaks south into Wyoming and west to Boulder River, the Livingston coal field, and to Electric coal field, there is little doubt that the lowest coal bed in these localities is equivalent to the coal found elsewhere between the two basal sandstones of the Eagle. It seems therefore that the series of sandy shales and sandstones, concerning which there has been considerable doubt, occurring between the lower of these two sandstones and the highest point at which Colorado fossils are known to exist, may be regarded with considerable confidence as belonging to the Telegraph Creek formation.

If this interpretation is correct, it is evident that the Telegraph Creek beds thin rapidly to the north, disappearing entirely before reaching the central part of the state, unless it should be shown that the zone of sandy shale everywhere found below the Eagle sandstone should be equivalent.

The variation in the thickness of the three subdivisions of the Colorado here used, indicates that there must have been a continued subsidence throughout Colorado time, since in all three cases the sediments are much thicker to the south than to the north. The total difference in the interval between the base of the Eagle sandstone and the base of the Dakota horizon at the Little Rocky Mountains (locality 24), as compared with that at Elk Basin, Wyoming (locality 11), is 1,544 feet, almost equal to the total interval at the first of these two points.

This difference in interval of 1,544 feet is slightly more at Elk Basin, Wyoming, than the total interval of 1,420 feet for the lower group, from the top of the Frontier to the base of the Dakota, at the same place. Is it not evident, therefore, that a subsidence must have occurred during Colorado time rather than before it? If a basin of rather restricted limits were forming, it is reasonable to assume that sedimentation would tend to be more rapid over the lowest part of the basin than elsewhere. Due to the greater occurrence of sandstones and sandy shales in the southern or basinward part of the area as compared to the northern and eastern part, throughout the Colorado shales, it appears that the southern part of the area must have been closer to a shore line. Under these conditions sedimentation was more rapid and of a different character over the slowly forming basin than in the north and east, where materials must have been transported for much greater distances and consequently in less volume. Thus the sea bed, by deposition at a more rapid rate in the one locality and lesser in the others, was kept at relatively constant horizon, so that beds of the same age were deposited throughout the Colorado sea but under different conditions. This is illustrated in the occurrence of sandstones from the Dakota throughout the Colorado shales and the lower part, at least, of the Montana group. Invariably there is a thinning of sandstone members to the north and east, as illustrated by the sandstones in the Mowry in the Big Horn Basin that are absent in Montana and by the larger number and greater thickness of sandstones in the Frontier group in the same locality, with the entire disappearance of some of these sands in short distances and the gradual thinning out of others before extending far east and north into Montana. In the case of the Eagle sandstone there are 200–400 feet of sediments assignable to that horizon in parts of southern Montana, which, as a mapable unit, does not extend anywhere east of R. 31 E. and is only represented by one sandstone member around the Little Rocky Mountains in northern Montana.

The subsidence must have continued through Colorado into Montana time, and while the Telegraph Creek beds and perhaps part of the sandy shales below the Eagle over central and northern Montana were being laid down, deposition was more rapid than at

any previous time, and the Montana sea either came in and mingled with the waters of the Colorado sea, or the Montana fauna began to appear and the Colorado fauna began to decline in the same waters.

As at previous epochs, sedimentation was more rapid over the area of subsidence, so that by Eagle time the sea bed had been built up to a relatively flat surface, on which the sandstones of true Eagle time were deposited. This diastrophic change and contemporaneous sedimentation permitted Montana fossils to occur far down in the Cody shales, producing the basis for a discussion which long remained unsettled. Washburne[1] correlated the beds assigned to the Mesaverde of the Big Horn Basin with the Eagle of Montana. Some years later Lupton[2] and Hintze[3] found fossils of undoubted Montana age 1,000 feet below the base of the Mesaverde. Hintze agreed with Washburne as to the Eagle and the base of the Mesaverde being equivalent, but showed that the Eagle could not be, in the Big Horn Basin at least, the base of the Montana group. Lupton felt that the lower part of the Mesaverde of the Big Horn Basin and the Eagle of Montana were not to be considered equivalent because fossils of Montana age were known to occur far below that horizon. If the interpretation here given is correct as to the history of the region, then Washburne and Hintze were correct in their interpretation relative to the time element and continuity of the deposition of the Eagle of Montana and the basal parts of the Mesaverde of the Big Horn Basin. The element entering into the question that caused confusion was that the Eagle had been considered the line of demarcation between Colorado time and Montana time. It appears, however, that over much of the area discussed, the Eagle is not the exact base of the Montana group, but occurs at a higher horizon, and that in the changing sea, sediments containing a Montana fauna were deposited long before Eagle time.

This subsidence and deposition had the effect of causing the Eagle sandstone to be deposited on beds younger in age from north to south. Hancock recognized this condition, for he said: "Southward from Billings to Bridger and thence to Cody on the west side

[1] C. W. Washburne, *U. S. Geol. Surv. Bull. 341.*

[2] C. T. Lupton, *U. S. Geol. Surv. Bull. 621-L*, pp. 173–74.

[3] F. F. Hintze, Jr., *Wyoming Survey Bull. 10*, pp. 22–30.

of the Big Horn Basin the sandy portion of the Colorado becomes much thicker, and the upper shale portion rises very rapidly in the stratigraphic column."[1] In other words, the Eagle climbed higher stratigraphically toward the Big Horn Basin than in northern Montana.

Here the question naturally arises as to deposition over northern Montana while the Telegraph Creek beds and their equivalent in the Big Horn Basin were being laid down. Inasmuch as no unconformity has ever been recognized between the Colorado shales and the Eagle sandstone, the only answer appears to be in the rate of deposition of sediments between northern and southern Montana. In the northern part there must have been a period of little deposition with an increasing amount southward until the point of maximum deposition was reached some place over western Wyoming.

The history of occurrences during the time interval covered by this paper, showing subsidence and contemporaneous deposition of sediments, seems to form the basis for some correlations previously indicated but not definitely suggested.

In the vicinity of Billings, Montana, there are about 200 feet of sediments that appear to be of Telegraph Creek age. On the Crow Indian Reservation there are about 320 feet; at Elk Basin, Wyoming, about 400 feet; and near Basin, Wyoming, about 1,000 feet of the upper Cody shales that appear to be of approximately the same age. It is probable, also, that the Steel shales of central Wyoming belong in part to the same series of beds.

The Eagle, characteristically marked throughout southern Montana by a coal bed between the two lowest sandstone members, indicates broadly similar conditions of deposition. Almost identical conditions in the basal part of the Mesaverde of the Big Horn Basin show depositions similar to that in the base of the Eagle. The fact that the horizon containing the coal in the base of both the Eagle and the Mesaverde can be traced from Montana as far south as Basin, Wyoming, leaves little room for doubt that they were deposited during the same time interval and under similar conditions.

The Elk Basin sandstone is thought to be a separate stratigraphic unit not correlated with any part of the Eagle, but rather

[1] E. T. Hancock, *U. S. Geol. Surv. Bull. 691*, p. 111.

occurring about the middle of the Telegraph Creek formation. A sandstone is found in the Lake Basin field at about the same distance below the base of the Eagle as the Elk Basin sandstone, and a sandstone is found at approximately the same stratigraphic position in the Telegraph Creek beds south of the Mifflin anticline on the Crow Indian Reservation, so that over southern Montana there is a sandstone of variable thickness and texture that appears to be equivalent to the Elk Basin sandstone, occurring in the Telegraph Creek formation.

SUGGESTED CAUSES OF DIASTROPHISM

At the beginning of Upper Cretaceous time, it has been shown that a subsidence probably began over southrn Montana and northwestern Wyoming and continued through Colorado into Montana time. During this time, as previously pointed out, sedimentation was taking place in that locality at a more rapid rate than elsewhere. Thus overloading began in the early Upper Cretaceous, probably contributing its force to a movement already started, and by the time of the deposition of the Eagle, it had accumulated a thickness of over 4,800 feet. If to this is added the thickness of earlier sediments, down to and including the Deadwood formation, of about 5,000 feet, there was a total thickness of beds of about 9,800 feet at the beginning of Eagle time. From Eagle time to the close of Wasatch time of Eocene age there were more than 10,000 feet of sediments deposited, so that at the close of the Wasatch there was a total thickness of about 20,000 feet over the area occupied by the Big Horn Basin. As far as known, from available information, there is no other locality to the north or east where there is such a thickness. In the vicinity of the Little Rocky Mountains, Collier and Cathcart[1] show a thickness from the base of the Deadwood formation to the top of the Bearpaw shales of 7,430 feet. If to this is added a maximum of 1,800 feet for the Lance and Fort Union formations of northeastern Montana,[2] the total interval would be about 9,200 feet at the close of Fort Union time. In the Black Hills to the east, the total thickness for the sediments from the base of the Dead-

[1] A. J. Collier and S. H. Cathcart, *U. S. Geol. Surv. Bull. 736*, pp. 172 and 173.

[2] A. J. Collier, *U. S. Geol. Surv. Prof. Paper 120*, p. 22.

wood formation to the top of the Fort Union could not have been over 11,000 feet when fully developed. There is no evidence that the Wasatch was ever present in Montana with the possible exception, perhaps, of a small area along the southern border of the state.

The absence of the Wasatch in Montana and the great thickness of the Fort Union beds near Red Lodge, of about 8,500 feet,[1] as compared to any estimated or known thickness elsewhere to the north and east, leaves little room for doubt that subsidence continued over southern Montana and northwestern Wyoming during Eocene time, and probably up to the time of the formation of the Beartooth, Absaroka, and Big Horn mountains.

Thus over southern Montana and northwestern Wyoming there appears to have been an overloading that gradually increased from Upper Cretaceous time until the close of the Wasatch of Eocene age that had an important bearing on the formation of the mountain ranges in that area.

In conclusion, the authors admit that other interpretations may be drawn from the data upon which this paper is based. It is expected that such may be the case. It is hoped, however, that further study along similar lines may stimulate continued effort, with the firm belief that by so doing a better understanding may be reached concerning the geologic history as it applies to stratigraphy and structure. A broad understanding of regional data, similar in character to those contained in this paper, may be of considerable importance, both from an economic and scientific standpoint.

DISCUSSION

R. S. KNAPPEN: It is notable that the thicker Colorado section occurs where the series is arenaceous. From the Wyoming boundary northward to Yellowstone River, delta sandstones occur between the Mowry and Telegraph Creek, the Torchlight and Peay sandstones thinning out and becoming almost indistinguishable. Since clays can compact 60 per cent or more on induration, while sands are compressed less than 10 per cent, it is probable that the present variation in thickness results from consolidation of the clays rather than contemporaneous down-warping of the pre-Cretaceous basement. At least one of the northward-extending thicker masses is more arenaceous than the thinner, adjacent "trough."

[1] E. G. Woodruff, *U. S. Geol. Surv. Bull. 341*, p. 94.

A. A. HAMMER: The occurrence of the coal in the Eagle sandstone indicates deposition in a relatively flat, fresh- or brackish-water basin. In northern Montana the total interval is about 1,780 feet, as between the base of the Eagle and the base of the Dakota. At Elk Basin the interval is about 3,300 feet, and near Basin, Wyoming, it is about 4,700 feet and only a very small amount of sand in proportion to the whole. If subsidence did not take place over the southern part of the area, how could 4,700 feet of sediments occupy the same interval as 1,780 feet and allow the deposition of the Eagle, with its coal beds, on a practically flat, fresh- or brackish-water lake or series of lakes of the same time interval? The rate of compression due to differences in character of sediments, even of 60 per cent, could not make the difference. The ratio of sandy materials to true shales in the two regional areas is not far different considering the total thickness in each locality.

GEOLOGICAL NOTES

PROTHRO SALT DOME, BIENVILLE PARISH, LOUISIANA

Bienville may now be classed with Winn as a salt dome parish of first rank in northern Louisiana. Already it claims four distinct domes on which the rock salt mass has been proved by drilling. The fifth dome, Prothro, has not yet been drilled, but it exhibits so clearly the characteristic surface features that it may safely be numbered with the other interior salt domes.

The two oldest and best known of the Bienville Parish domes, in so far as they may be reckoned in human history, are Rayburn's, in Sec. 31, T. 15 N., R. 5 W., and King's, at the village of Castor, in Secs. 34 and 35, T. 15 N., R. 8 W. Both were old deer licks, undoubtedly frequented by the Indians in hunting and camping. Later, during the Civil War, they were the centers of great activity as salt works. Harris and Veatch[1] have summarized and augmented the earlier published information on these localities. The salt cores of both structures have been determined by wells drilled in search of oil and gas.

The two most recently discovered domes where the salt mass has been proved by drilling are Arcadia, in Sec. 29, T. 18 N., R. 5 W., near the town from which it was named, and Vacherie, in Sec. 21, T. 17 N., R. 8 W., east of the village of Heflin. These two domes differ from Rayburn's and King's in that they lack the open salines at the surface, and in fact are so deeply buried that their presence was not suspected until comparatively recent years, when more detailed geological work was done in this part of the state. J. Y. Snyder, of Shreveport, became interested in geological conditions at Arcadia and with his drilling associates in August, 1922, discovered rock salt at a depth of 1,405 feet.

Vacherie was also found to be a salt dome in August, 1922, when the Standard Oil Company of Louisiana, drilling in Sec. 16, T. 17 N., R. 8 W., Webster Parish, struck rock salt at 799 feet. This discovery was made as

[1] G. D. Harris and A. C. Veatch, "A Preliminary Report on the Geology of Louisiana," *Geol. Surv. of Louisiana, Report of 1899*, pp. 52–55, 63–64, 122–24.

A. C. Veatch, "The Salines of North Louisiana," *Geol. Surv. of Louisiana, Report of 1902*, pp. 71–80.

a result of the field work of S. C. Stathers, chief geologist for the company, who found an inlier of Arkadelphia shale in a shallow water well in an Eocene area. The second test hole was drilled just across the line in Sec. 21, Bienville Parish, where the salt was found at a depth of 777 feet, the highest part of the salt body.

The fifth and most recent of Bienville's domes to receive general recognition as a typical salt dome, although not yet actually drilled, is Prothro, located in Secs. 7 and 18, T. 14 N., R. 6 W., 4 miles northwest of the town of Saline on the Louisiana and Northwest Railroad. In July, 1922, the writer, in company with J. L. Dorman, lawyer of Shreveport, visited this very interesting abrupt Cretaceous cropping within Eocene sands. Mr. Dorman was once a resident of Saline, Louisiana, where he had become familiar with the locality and had recognized the unusual character of the rocks exposed. Why this truly remarkable exposure was not brought to the attention of the early geologists who worked in Louisiana is difficult to understand, and how it has subsequently escaped the picks of many oil company geologists and the drills of countless wildcatters is still more remarkable than the outcrop itself, unless it be that latter-day geologists do not publish all they know, and that interior salt domes are no longer popular with oil producers. At any rate, it seemed not to have been visited by the local profession and no published notice of it had ever been made.

In February, 1924, Sidney Powers and W. C. Spooner, collecting material in their work on interior salt domes of Texas and Louisiana, accompanied the writer to Saline, and the name Prothro, from Prothro Mill Creek, located on the dome, was agreed upon. This latest addition to the interior salt domes of Louisiana has been recently studied and described in detail by Mr. Spooner, who has included it in his paper on "Salt Domes in Northern Louisiana," which, together with Mr. Power's paper on "Interior Salt Domes of Northeast Texas," was scheduled for the Houston (1924) meeting of the American Association of Petroleum Geologists.

Half-hidden by the shifting sand along Gunnegan Branch, but sharply protruding from the surface a few hundred feet up the hill slope in a little pine thicket, only a stone's throw from the old highway between Saline and Bienville, several excellent exposures of greenish-gray calcareous sandstone and white chalk containing Upper Cretaceous fossils meet the astonished eyes of the observer, who has noticed only deep beds of Eocene sand not more than a mile away in either direction. The Cretaceous exposures occur in an area only a hundred yards square. Their attitude

is almost vertical, with the suggestion of a very steep dip west-southwest, the strike being north-northwest. They are located in the middle of the west side of a pronounced topographic rim which surrounds a low central area of swamps and salt licks, except where drainage from this low center passes through the rim to the east into Saline Bayou. Quaquaversal dips exposed in the surrounding Eocene correspond in general with the topographic outline of the dome, which is elongate north-northwest and south-southeast. Topography and stratigraphy combine in the delineation of this truncated structure more clearly than in any other North Louisiana dome.

An additional and important fact about this long-ignored but clearly defined dome is the extent of deformation undergone in its making. Through beds of unconsolidated Claiborne sands of middle Eocene age has been thrust hard Upper Cretaceous sandstone of Bingen[1] age from a depth of almost 3,000 feet. These beds, exposed on Prothro, are much older than any exposed on domes to the north, up the regional dip nearer the outcrop of Cretaceous formations.

Another leading fact brought out in the study of this dome is the presence of igneous material such as volcanic tuff[2] in the Bingen rocks here exposed. This bears on the general problem of volcanic activity in the region, although it probably does not have any direct relation to the origin of salt domes, since similar material is found at the same horizon in this formation throughout the greater part of North Louisiana and South Arkansas.

J. P. D. HULL

SHREVEPORT, LOUISIANA
May 19, 1925

A METHOD FOR CORRELATING GUMBOS

Neutral-colored plastic clays, usually referred to as gumbo, and found in great abundance in the Mesozoic and Tertiary of the coastal plain bordering the Gulf of Mexico, have few characteristics which have any value in correlation problems. For this reason they are commonly only recorded by the person logging deep wells as hard, soft, or sticky, gumbo, with a notation as to inclusions, such as streaks of sandstone or limestone.

[1] L. W. Stephenson, quoted in letter from the Director of the U. S. Geol. Survey, August 21, 1922.

H. D. Miser and C. S. Ross, letter, July 22, 1924.

[2] H. D. Miser and C. S. Ross, "Volcanic Rocks in the Upper Cretaceous of Southwestern Arkansas and Southeastern Oklahoma," *Amer. Jour. Sci.*, Vol. IX (February, 1925), p. 123.

Little is found in published accounts of the lateral extent of these clays, but from the characteristic fineness of particles which gives them a high plasticity it may be concluded that they are apt to be of wide lateral extent. A lack of prominent characteristics has led to a general disregard of these beds, so that it is often necessary to go to great depths before a key bed can be found. The writers, following a suggestion of Professor E. C. Case, of the University of Michigan, that colloid content might be of value, have been experimenting with a method which shows some promise of being useful in distinguishing and correlating the gumbo beds. It has been difficult to obtain cored samples of gumbo, and this preliminary notice is being prepared with the hope that it will lead to a collecting of samples upon which further work can be done.

Recent advances have been made in the measurement of colloidal content of soils. Professor George Bouyoucos,[1] of the Michigan State College, has announced that the heat of wetting which develops as water is added to a finely divided, artificially dried soil is a measure of the colloidal content. He also found a range of colloidal content in different soils, varying between 17.67 per cent in Rhode Island sandy loam, and 70.56 in a clay from the Upper Peninsula of Michigan. The method which he used involved a determination of the heat of wetting of a sample of the soil, the extraction of some of the colloidal material, and a determination of the heat of wetting of the extracted colloids. In the present experiment it was not the purpose to find the exact amount of colloids present, but rather to find if colloids of a similar amount of activation were present in different areas of the same bed, and if they were present in quantities great enough to be easily measurable. As a test of the feasibility of this sort of measurement for purposes of correlation, it was decided to attempt only the measurement of the heat of wetting of a given quantity of gumbo, eliminating the extraction of the colloidal material, and thus obtaining a measure of the colloidal action which would probably depend upon both the kind and the quantity of colloids present. This decision was based upon the hope that a diagnostic character of the sediment could be revealed which would not need the elaboration necessary to obtain an actual measurement of the amount of colloids present.

Great difficulty was experienced in obtaining samples of cored gumbos, although a number of oil companies generously supplied samples. Such cores as have been saved usually have been accidentally preserved on account of their proximity to some layer more desirable for correlating, or to some bed which carries oil showings, and it is rarely possible to obtain

[1] *Soil Science*, Vol. XIX, No. 2 (February, 1925), pp. 153–62.

samples from an identical bed in several adjacent wells. The most complete set of samples was sent by Donald C. Barton, chief geologist for the Rycade Oil Corporation, who also sent logs of the wells from which they were obtained and a determination of the approximate extent of the Miocene, Oligocene, and Eocene, as determined from a study of fossils. Unfortunately, a lack of key beds made it impossible for the company geologists to give an exact statement of the identity of the different beds in the several wells. For that reason the results of this preliminary experiment are not definite, although they seem to offer promise of worthwhile results which should be tested with samples taken at several different places from horizons of known identity. An attempted correlation obtained by plotting the logs of the wells, the paleontological determinations, and the waters encountered led to the supposition that a sample from the well, Gray No. 1, Matagorda County, Texas, at 3,291 feet, and a sample from a nearby well, Hudson No. 1, at 2,781 feet, came from the top of the same bed, which in this case was a brown and red clay, contrasting in color with the usual gray shales, and that a sample from 3,770 feet in Gray No. 1 came from the bottom of a bed of hard plastic clay which yielded a sample in Hudson No. 2 at 3,650 feet, the top of the same bed. The geologists of the Rycade Oil Corporation could not confirm this correlation, although they stated that it did not conflict with data which they had. The results of tests show the following remarkable correspondence (Table I) in the heat of wetting developed in the samples from the beds which were believed to be identical:

TABLE I

Well	Depth of Sample (Feet)	Heat of Wetting (Calories/gm.)	Well	Depth of Sample (Feet)	Heat of Wetting (Calories/gm.)
Gray No. 1.....	3,291	5.8	Hudson No. 1	2,781	5.1
Gray No. 1.....	3,770	13	Hudson No. 2	3,650	13

The samples from 3,291 feet in Gray No. 1 and 2,781 feet in Hudson No. 1 were similar in appearance and quite uniform throughout, but the sample from 3,770 feet in Gray No. 1 contained sand and cherty fragments, as well as a few lumps of what appeared to be a uniformly fine grained gumbo. These lumps, similar in appearance to those from 3,650 feet in Hudson No. 2, were selected for the test.

The accurate determination of the heat of wetting was worked out entirely by the junior author, who has prepared the following account of his method:

The material was ground until it was not gritty to the teeth, spread on a watch glass, and heated in an oven for 24 hours at 115 degrees C. About 10 gm. of it was placed in a thin-walled blown-glass bulb of known weight having an inside diameter of about 22 mm., heated again for an hour at 115° C., and then sealed off. The weight of the bulb and the contained material was next obtained, after which it was placed in a calorimeter of the adiabatic type, using water in the outside bath and a vacuum bottle with wide mouth fitted with a rubber cork for the inside vessel. Through the cork were passed a Beckman thermometer, an apparatus for breaking the glass bulb containing the material for testing, a stirrer, and lead-in wires for a thermo-element. It was found necessary to have all parts leading into the bottle either made of glass or surrounded by glass tubes. The thermo-element was made of manganin wire, the resistance of which varies but slightly with changes in temperature. The outside bath was equipped with a stirrer, a thermo-element of about 500 ohms resistance, and a brass tube through which had been drilled several holes. This tube, used for admitting hot or cold water, passed around the bottom of the bath with both ends leading out at the top, making it possible to change the temperature of the bath very quickly. The calorimeter had been calibrated by using a current from a 4 volt, 80 ampere-hour lead storage battery giving a constant current, connected in series with a rheostat, standard resistance, ammeter, and the thermo-element in the vacuum bottle. The resistance of the thermo-element was determined by a comparison of drops in potential over the thermo-element and the standard resistance, using a type K potentiometer (Leeds and Northrup), connected by a double throw switch.

After all the parts were placed in the vacuum bottle it was filled three-quarters full of distilled water, the stirrers were started, and the temperature was brought up to a certain point. The bulb was then broken and the difference in temperature noted after a ten-minute interval, the rise in temperature being due to the heat of wetting plus that due to stirring. After another ten-minute interval the rise in temperature was again noted and taken as a measure of the heat due to stirring. Next the current was turned on for five minutes, adjusted so that the drop of potential over the thermo-element was about one volt as indicated on the potentiometer. The temperature was read after ten minutes, giving the change in temperature due to letting the current run for five minutes and the stirrer operate for ten minutes. During the flow of the current the drop of potential over the thermo-element and that over the standard resistance were noted, so that the resistance of the thermo-element could be calcu-

lated by proportion. Throughout the experiment the temperature of the outside bath was constantly adjusted so that it would be the same as the temperature inside the vacuum bottle.

The heat of wetting can be calculated from the observations thus made. According to Joule's law:

$$H(\text{calories}) = .238\ I^2Rt$$

where I is current in amperes, R, resistance of the thermo-element, and t is time in seconds.

$$\text{But } I = E/R \text{ and } I^2 = E^2/R^2, \text{ so } H = .238\ E^2t/R.$$

If we add a known amount of heat and note the temperature rise due to it, and then note the temperature rise due to an unknown amount of heat, the amount of the unknown can be calculated by proportion,

$$H'/H = T'/T$$

where H' and T' are the unknown amount of heat, and the rise of temperature due to it and H and T are the known amount of heat and the corresponding rise of temperature.

Substituting the value for H, given above, in the last equation, we have

$$H' = .238\ E^2tT'/RT,$$

the amount of heat of wetting produced by the material, and dividing by the number of grams of material we have the heat per gram.

If there is considerable variation in the heat of wetting of gumbos, as the present experiment seems to show, a much simpler type of calorimeter and a much shortened procedure may be developed which could be adapted to field laboratory conditions.

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[1] Published by permission of Acting Director, U.S. Geological Survey.

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BERTRAND L. JOHNSON AND L. M. JONES

The Origin of Continents and Oceans. By ALFRED WEGENER, translated from the third German edition by J. G. A. SKERL, with an Introduction by J. W. EVANS. London: Methuen & Co., Ltd. 1924.

The theory of the displacement of the continents, the details of which have been largely worked out by Professor Wegener, is not at this writing entirely

new, but it has never before been fully presented in English. The translation of J. G. A. Skerl is well written, the arguments are well presented, and on the whole it sets forth the author's original views. Apparent omissions of many possible criticisms of details pertaining to the proposed theory will, at least in part, be dealt with by the translator in a separate writing.

Those who have not read the displacement theory in its earlier form will find food for thought in this text; and promise for those who have read either of the first two German editions of Wegener is found in the following quotation from the author's Preface: "The third edition is again completely revised and certainly differs as much from the second as that did from the first."

The text in itself is a review of facts, the interpretation of which are applied to support this theory. It is therefore difficult to do more than barely outline the substance of this text in a review.

The displacement theory postulates a difference in the composition of the earth's crust; the *sial* (Si+Al) representing the continental masses; and the *sima* (Si+Mg) representing the substratum of the ocean bed. The magma from which the *sial* originally crystallized owed its fluidity to a very large amount of magmatic water and other volatile materials, and after these were once lost in the course of crystallization, a temperature higher than that of the original magma is required to bring it once more into the fluid state.

Basic magmas contain less water, and there is less difference between the temperature of the original crystallization of the rock and that required for remelting. The *sima* could therefore be more easily rendered molten or semimolten. This *sima* is the postulated semifluid or viscous, ferric, or basaltic zone in which the masses of the lighter *sial* may be likened to floating icebergs.

The *sial*, according to Professor Wegener, once covered the surface of the globe, but as the result of folding, it increased in thickness and diminished in area, until in late Paleozoic times it formed a vast land referred to as *Pangaea*. This mass subsequently separated and drifted apart to form the present continents.

The proposed drifting of continental masses may, to the too causual reader, be regarded as a hypothesis too speculative to be worthy of attention. The evidence brought to bear on this subject, however, is extensive in its range, clearly set forth, and supported by a striking soundness of reasoning.

The displacement theory agrees with the doctrine of isostasy, and contradicts the older contraction or shrinkage theory. It is supported by geophysical, geological, paleontological, paleoclimatic, and geodetic arguments. Probably the best known of these arguments relates to the complementary outlines of the coasts of Africa and South America. This general phase of the argument includes, in this edition, discussions of the coastal margins of all the continents, the apparent relation of tectonic or trend lines on separated shores, the relation of faunas prior to the supposed separation, and the evidence bearing on the migration of the poles applied to this theory of continental drift.

The first part of the book is given to the essentials of the displacement theory; the second part to "Demonstration," or the interpretation of evidence

in the light of this theory; the third part, "Elucidation and Conclusions," is more or less an application of the theory.

One of the many interesting minor hypotheses supported by the displacement theory is the postulated relation between regression, transgression, and the wanderings of the poles. During the wandering of the poles called for by Wegener's hypothesis the earth lags in the alteration of its shape, while the ocean adjusts itself immediately. At this time regression must prevail in front of the wandering pole, and transgression behind it. This, of course, applies only to the major transgressions and regressions and not to all the minor variations.

The fundamental principles of the displacement theory are rapidly being accepted by European geologists, and its application may be found in nearly all new literature on Alpine tectonics.

There is a vast field for criticism, and as well a vast field for co-operative ideas. That the theory in its entirety will live is hardly possible; that the principle of the theory will grow into general acceptance is quite probable.

D. H. Thornburg

BASEL, SWITZERLAND
Feb. 23, 1925

Block Diagrams and Other Graphic Methods Used in Geology and Geography. By ARMIN KARL LOBECK. New York: John Wiley & Sons, Inc., 1924. Pp. 206, figs. 288.

One of the past presidents of the American Association of Petroleum Geologists concluded a short discussion of the essentials of a geological report with the advice: "Say it with pictures." There can be no quarrel with this suggestion. If the report is designed to serve a scientific reader, illustrations that are appropriate will greatly strengthen and clarify the presentation; if it is designed to serve a layman who is not familiar or only moderately familiar with geology, graphic presentation is the most certain method to convey the essential information. It is true that a few rare individuals have the power to paint word-pictures that are so clear, and so independent of scientific terminology, that they meet the requirement specified by Rollin D. Salisbury, who stipulated that a statement should be more than understandable—it must not be misunderstandable. This talent for word-pictures is worth striving for, but for most of us it is far less attainable than the ability to convey ideas graphically. This does not necessarily mean ability to do real artistic work nor call for the utmost precision of drawing. In fact, Lobeck, in the book under review, states that "detailed precision of form and mathematical exactness of position is not necessary, nor even desirable."

Most geologists use sketches and diagrams in their notebooks, but these are for their own use, and few attempt to incorporate them in finished reports. The obvious reason is that the sketches are so crude that one fears they will detract from rather than enhance the value of his product. Yet the principles that will permit a fair amount of skill in drawing sections, block diagrams, and landscapes are surprisingly simple, and it seems safe to predict that nine out of ten

geologists could master those principles with no more effort than it takes to become proficient with plane table and alidade.

Lobeck's book on *Block Diagrams* is, in the opinion of the reviewer, the best manual for self-instruction in the art of graphically presenting features of geology and topography that has appeared. It is carefully and understandably written; the pupil is taken from one stage to another logically and easily, and he can begin to use his newly acquired knowledge effectively and profitably by the time he has carefully gone through the Introduction and chapter II, which is a presentation of one-point perspective. In fact, after he has studied the next two chapters as well, and learned the principle upon which two-point perspective is based, and how to portray simple topographic and structural types, he will be in a position to go ahead independently and can, if necessary, develop his own technique on more complex structural and physiographic subjects, although he will do well to follow the text through its excellent expositions of how to prepare block diagrams of dome mountains, folded mountains, block mountains, streams, etc. The oil geologist will find the chapters on dome and folded mountains particularly helpful.

A second part of the book that deals with the solution of problems in structural geology by means of isometric diagrams seems less practical. Like most graphic solutions of structural problems, they are of questionable importance to the man who has not a great amount of that type of work to do.

The oil geologist will rarely attempt a very elaborate and time-consuming illustration. Unless one has a talent for illustration, the attempt is hardly apt to repay the effort expended. Accordingly, it is anticipated that Section III of Lobeck's book which deals with special methods and elaborate types of diagrams will be used much more by the professional draftsman, and by the illustrator who is willing to spend much time to improve his technique, than it will be by the geologist and the engineer. However, it is of value and interest if only to show what can be done in the way of portraying large areas and complex conditions, and making an illustration take the place of a model.

A chapter that deals with landscape sketching will receive the hearty interest and approval of the geological students of this book. It might be called a chapter on field methods, for it is largely devoted to the operations actually followed when sketching in the field, using the principles presented in the earlier chapters. The illustrations used to give point to the text depict many features that the field man will recognize as variations of topographic forms that may logically appear in his own notes and reports.

The final chapter in the book deals with methods of crystal drawing and naturally will appeal almost exclusively to students of mineralogy. This, like the chapter on solution of problems by means of isometric diagrams, is for the office man with drafting equipment who makes a specialty of graphic methods and will be little used by the oil geologist.

This book is welcomed as an effective aid to the oil geologist in his duty to convey information simply and understandably to both laymen and scientists.

K. C. HEALD

THE ASSOCIATION ROUND TABLE

THE OKLAHOMA GEOLOGICAL MAP

Following is a statement of the distribution of funds raised to permit the compilation and publication of an areal geological map of Oklahoma by the U. S. Geological Survey through the co-operation of the National Research Council which acted as treasurer for funds raised privately.

STATEMENT, JUNE 9, 1925

RECEIPTS:		
Subscriptions	$3,396.25	
Interest on bank deposit	37.93	$3,434.18
DISBURSEMENTS:		
Drafting in Tulsa	$ 569.95	
C. W. Shannon, compilation, etc.	176.28	
National Research Council	2,543.58	
Balance, Security National Bank of Tulsa	144.37	$3,434.18

Total cost of the field work and cost of publishing preliminary edition, exclusive of salaries and other expenses borne by the U. S. Geological Survey, was $3,289.81. This edition, scale 1:300,000, with brown lines and no colors, was distributed December 20, 1924, to those who assisted in the compilation. The total number of subscribers was 260. Solicitation of funds was exclusively from geologists, but subscriptions were accepted from oil operators and companies when sent at the direction of geologists employed by them.

The preliminary edition, published in order to secure revisions of formation boundaries, is exhausted. The final edition in colors is being printed by the U. S. Geological Survey and will be sold by them at a nominal charge. Final revision was not completed until June, 1925, and the printed map is expected early in 1926.

Funds remaining in the treasury will be turned over to the National Research Council for use in further areal geological work in Oklahoma by the U. S. Geological Survey. No additional subscriptions will be solicited.

In submitting this report, the Treasurer cannot refrain from expressing his appreciation of the U. S. Geological Survey's splendid co-operation in this project, and particularly of assistance given by Mr. W. C. Mendenhall, chief geologist, and Mr. H. D. Miser, whose painstaking work has rendered this map an ideal whose multiplicity of detail probably no other map of similar areal

extent has ever attained. Acknowledgments should also be made to the wholehearted generosity, both with information and with financial support, of the geologists working in Oklahoma.

SIDNEY POWERS, *Treasurer*

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following applicants for membership in the Association. This publication does not constitute an election, but places the names before the membership at large. In case any member has information bearing on the qualifications of these applicants, please send it promptly to Charles E. Decker, Norman, Oklahoma.

(Names of sponsors are placed beneath the name of each applicant.)

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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

ERNEST GUY ROBINSON, formerly geologist with the Midwest Refining Company in Montana, is now in charge of the San Antonio district, southwest Texas, for the Roxana Petroleum Corporation.

JUN R. TAKAHASHI, associate professor of the Imperial University of Tohoku, Japan, writes from Paris that for some two years he has been making an extended study of various oil fields. After about six months in California, he visited Colorado and Pennsylvania, and in Europe has been making special study of the oil fields of Alsace, Italy, France, Tunis, and Algeria. After examination of the oil shale mines of Scotland, he plans to visit oil fields in Germany, Poland, and Rumania, and to return to America.

B. KOTO, professor of geology at the Imperial University at Tokyo, the first Japanese member of our Association, has recently retired from this position after some thirty years of service. Professor Koto is succeeded by Professor T. Kato, who is now with Mr. Takahashi in France and is planning shortly to visit in America.

W. T. THOM, JR., chief of the fuel division of the U. S. Geological Survey, Washington, D.C., devoted a week in the latter part of May and early June to an inspection trip in the Shreveport, Louisiana, territory, with particular attention to the Webster Parish oil and gas fields. C. H. DANE, also of the fuel division, has spent several weeks on detailed subsurface structure in Louisiana.

H. N. SPOFFORD, consulting geologist, Box 1836, El Dorado, Arkansas, visited Shreveport, Louisiana, in June, in the interest of wildcat work in the Louann, Arkansas, district.

H. D. EASTON, who has a consulting office at 304–6 Ardis Building, Shreveport, Louisiana, is the author of an article entitled "Smackover Formations Suggest Relation to Monroe," in the *Oil Weekly*, issue of June 5, 1925.

The Shreveport Geological Society held its third annual field excursion June 13 and 14. This year's trip covered 200 miles through the Cretaceous and Paleozoic outcrops of southwestern Arkansas, starting from Hope, passing through type localities at Saratoga, DeQueen, and Dierks, and ending at Nashville, Howard County. Two formations which drew particular interest this year were the Annona chalk, correlated in part with the Pecan Gap chalk of Texas by some geologists, and the DeQueen limestone outcrops, which are

probably equivalent to part of the Glen Rose formation which produces high gravity crude in the deep Pine Island pool of the Caddo, Louisiana, field. This year's party included forty-four people from Arkansas, Louisiana, Oklahoma, Texas, and the U. S. Geological Survey. Sixteen automobiles furnished transportation.

The officers of the Shreveport Geological Society are W. E. HOPPER, president, W. C. SPOONER, vice-president, and H. G. SCHNEIDER, secretary and treasurer. The committee in charge of the third annual field trip consisted of JOHN S. IVY, chairman, J. P. D. HULL, and L. P. TEAS.

H. V. HOWE, head of the department of geology at Louisiana State University, Baton Rouge, has completed his spring-term extension course of lectures in graduate geology at Shreveport, Louisiana, sponsored by the Shreveport Geological Society. These lectures covered the Eocene formations of the Gulf Coastal Plain, being a digest of the literature with additional data from the personal study of Professor Howe and the field work of a number of geologists who subscribed to the course. It is expected that the university will issue bulletins summarizing these lectures by formations.

GEORGE C. BRANNER, state geologist, Little Rock, Arkansas, exhibited a large wall map showing the areas of Arkansas, mapped and unmapped geologically, at a meeting of the geologists composing the Arkansas field trip of the Shreveport Geological Society, held June 13 at Hotel Luton, DeQueen, Arkansas.

ELTON RHINE, representing the geological department of the Empire Gas and Fuel Company of Bartlesville, Oklahoma, has opened an office at 714 Ardis Building, Shreveport, Louisiana. Mr. and Mrs. Rhine are living at 414 Gladstone Boulevard, Shreveport.

RAYMOND M. CARR, who until recently has been with the Bureau of Mines at Eureka, Kansas, has accepted a position with the Sinclair Oil and Gas Company as resident engineer in the Garber, Oklahoma, field.

E. T. DUMBLE, consulting geologist for the Southern Pacific Company since 1897 and organizer and manager of its subsidiary oil companies, having passed the prescribed age limit for active service, retired June 1.

REGINALD C. STONER has been made assistant general manager of the Producing Department of the Standard Oil Company of California. He will have his headquarters at San Francisco.

The field work for the new topographic maps, which has been carried on jointly for the last three years by the U. S. Geological Survey and the county of Los Angeles will be completed in about one month. These maps, which are on the scale of 1 inch to 2,000 feet, with 5-foot contours, will be of great benefit to all geologists working in Los Angeles County.

JOHN P. BUWALDA, professor of geology at the University of California, has accepted the position of head of the department of geology which is to be established at the California Institute of Technology, located at Pasadena.

J. B. UMPLEBY is sailing on the S.S. "Paris," on July 18, for Hanover and Pechelbronn, to study oil mines, and from there will go to take up the study of the Scottish oil shales.

FRANK BUTTRAM and family are spending the summer in Europe.

D. W. OHERN, president of the Oklahoma City Rotary Club, has just returned from the International Convention of Rotary Clubs at Cleveland.

W. C. KITE is doing field work in the Wichita Falls area.

WALTER A. VER WIEBE is working for the Michigan Geological Survey during the summer. Following work on the stratigraphy of Alpena County, he plans to start on Menominee County. During the coming year he will teach again at the University of Michigan, giving a course entitled "The Stratigraphy of Petroliferous Areas."

FREDERICK G. CLAPP, who went to Australia late in 1923, has been engaged in a careful search for oil in Australasia, visiting most of the critical geological localities of Australia and New Zealand, with some attention to possibilities elsewhere in Australasia. Meanwhile Teranaki Oil Fields Limited has been organized on his advice; two wells were started this year in Taranaki, New Zealand, and one of them is now a 5,000,000 gasser at 1,555 feet.

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